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Metals and Alloys

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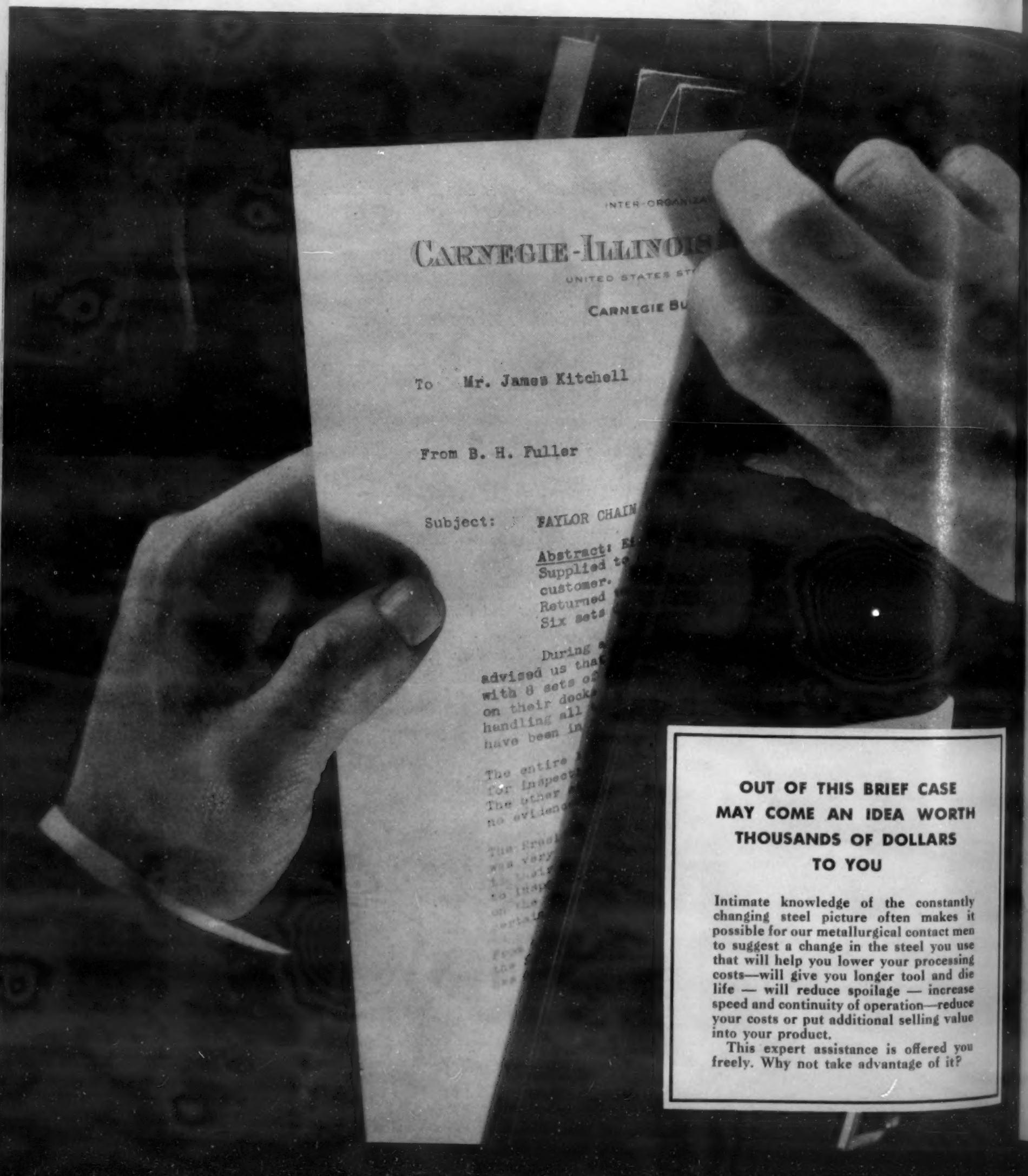
The *"best"* steel you


CARNEGIE-ILLINOIS
To Mr. James Kitchell
From B. H. Fuller
Subject: TAYLOR CHAIN
Abstract:
OUT OF THIS BRIEF CASE
MAY COME AN IDEA WORTH
THOUSANDS OF DOLLARS
TO YOU
Intimate knowledge of the constantly changing steel picture often makes it possible for our metallurgical contact men to suggest a change in the steel you use that will help you lower your processing costs—will give you longer tool and die life — will reduce spoilage — increase speed and continuity of operation—reduce your costs or put additional selling value into your product.
This expert assistance is offered you freely. Why not take advantage of it?

Ten Years' Progress

In the Preview section of this issue, pages A23 to A79, we desire to call special attention to a series of some 30 reviews of metallurgical progress in the last ten years. It is entitled—"Ten Years of Metallurgical Progress Reviewed—1929 to 1939." In this our readers will find an impressive discussion of this progress in many major fields, written by members of the Editorial Advisory Board, the editorial staff and a few prominent leaders in other fields. These men speak with the highest authority.—E. F. C.

Robert Henry Thurston

On October 25 there will be celebrated at Cornell University, the 100th anniversary of the birth of R. H. Thurston, the first director of the Sibley College of Mechanical Engineering at Cornell. We were late in making editorial comment on the Gibbs centenary earlier in the year; we'll catch the boat on this one. As it happens, Gibbs and Thurston both rendered great service to metallurgy, but in quite different ways. Gibbs dealt with theory and didn't in the least care whether anyone applied it or not. It was left to others to demonstrate experimentally that the phase rule was helpful in the study of metals. Thurston was a doer, who wanted to know what metals were good for as materials of engineering, and who found out, by study of what metallurgical literature existed in his day as far as that gave information, but who energetically filled the gaps by his own experiments, often devising or improving testing equipment and methods in his quest for information.

The son of a builder of steam engines, he was graduated from Brown at the age of 20, worked in his father's plant, served in the Engineering Corps of the Navy during the Civil War, then taught at Annapolis, was called to the chair of Mechanical Engineering at Stevens Tech. on its foundation, then guided the destinies of Sibley College from its inception till his death. He was not only an administrator and teacher, but an active investigator and a prolific writer. Some 300 books and articles from his pen covered a wide variety of fields, with special attention to the steam engine, friction and lubrication, and metals as materials of construction.

For a dozen years, both while at Stevens and at Cornell, he was the moving spirit and did the experimental work for a U. S. Commission or Test Board, set up to secure engineering data on iron, steel, and non-ferrous metals for the Navy and other government users of metals. The reports of this work, though long out-dated by other more precise studies, (many of which were set in motion by the impetus of Thurston's work), are still of interest, though so long out of print that the young metallurgist of today can hardly procure them for his shelves.

For example, long before the days of high test cast iron, Thurston cited a 3.12 C, 1.34 per cent Si iron "toughened by addition of wrought iron scrap," with a tensile strength of 50,000 lbs. per sq. in. and drew definite conclusions as to the strengthening effect of a lowering in carbon. Data were so scanty in those days that it was not unusual to print a complete test log of a tensile test, giving the extensometer reading for every increment of load. The phraseology sounds a bit quaint when read today, but Thurston's appraisals of the true implications from scanty and conflicting data are astonishingly good.

In his study of the brasses and bronzes, Thurston went over the whole Cu-Zn-Sn series in a systematic way. This was perhaps the first complete metallurgical study of a ternary series. He plotted his data on a ternary diagram, probably its first use in metallurgy, and using this as a base, made up solid diagrams to show the tensile strength. The peaks and valleys corresponded nicely with the phase changes when they were later determined according to Gibb's principles.

Thurston's fame as a mechanical engineer was so great that one does not at first think of him as a metallurgist, but much of his important work was in metallurgy. He was an active member of the A. I. M. E. and he may fairly be classed as one of the pioneer metallurgical engineers, a leader in the search for information on the properties of metals with the intention of putting that information to immediate engineering service.—H. W. G.

One section of the Simonds foundry showing the pouring floor in the foreground and the Ajax high-frequency furnaces on the right. The two 600-lb. capacity units are clearly shown while the two 100-lb. furnaces may be seen in the background. In the extreme background is a section of the snag grinding department.

A corner of the casting foundry. Some of the molding machines are visible in the immediate foreground. The modern sand conditioning equipment may be seen in the background.

"Alnico" and Related Alloys

— The Metallurgical Story

by EDWIN F. CONE

FOR MANY YEARS STEEL MAGNETS have been necessary for various types of equipment. In the early days, the demands for such a steel were of a decidedly different character than they are today. As new types of equipment, involving magnet steels, were perfected, demands for a permanent magnet steel developed and increased. This tendency has been progressive so that a permanent magnet steel that would meet conditions 10 years ago, was unequal to those later. Thus it has been necessary for the metallurgical engineer and the metallurgist to perfect new and stronger permanent magnets. They have been equal to the task, though accidental discovery has in some instances been the case.

Development of Magnetic Alloys

Various steps in this progressive development include briefly the plain carbon magnet steel, then the manganese magnet steel, followed by the low and high chromium (2, 3.50 or 6%) steels. Overlapping or coincidental with these steels was the 5 per cent tungsten steel and also the low and high cobalt grades (3 to 9% Co). These are the Co-Cr type containing no tungsten. They were developed in England and required a triple heat treatment to bring out their properties. Darwin and Milner in England did a fine job with these compositions containing 3 to 15 per cent Co and these steels, given the proper triple heat treatment, develop a higher coercive force than is possible in types made in this country containing tungsten and having the same amount of cobalt. The residual values, however, in the cobalt-chrome type of steel were very much lower than are developed by our tungsten-bearing types used in this country, and this, together with the difficulty in giving the triple heat treatment probably has limited the use of these steels in this country to quite an extent.

About the same time came the cobalt-chromium-tungsten steels and the high cobalt types, 37 to 41 per cent Co. Many of these steels were permanent magnet grades but the best were at least equaled or surpassed by those now known as the "Alnico" types—especially suited for uses to which some of the earlier ones were not.

The Alnico Alloys

These new nickel-aluminum-iron alloys, with or without other additions ("Alnico and Alnic"), are credited to a Japanese metallurgist, T. Mishima, and to the General Electric Co., though Mishima found this type experimentally. After the negotiations which frequently accompany such developments, the General Electric Co. finally obtained the sole rights in the United States and licensed certain producers.

The first of these was the Simonds Saw & Steel Co., Lockport, N. Y. This was about 5 years ago, since which time the company has had a wide experience in their production. The writer was accorded the privilege of visiting this plant in order to write a description of the metallurgy and heat treatment of these alloys, as developed there.

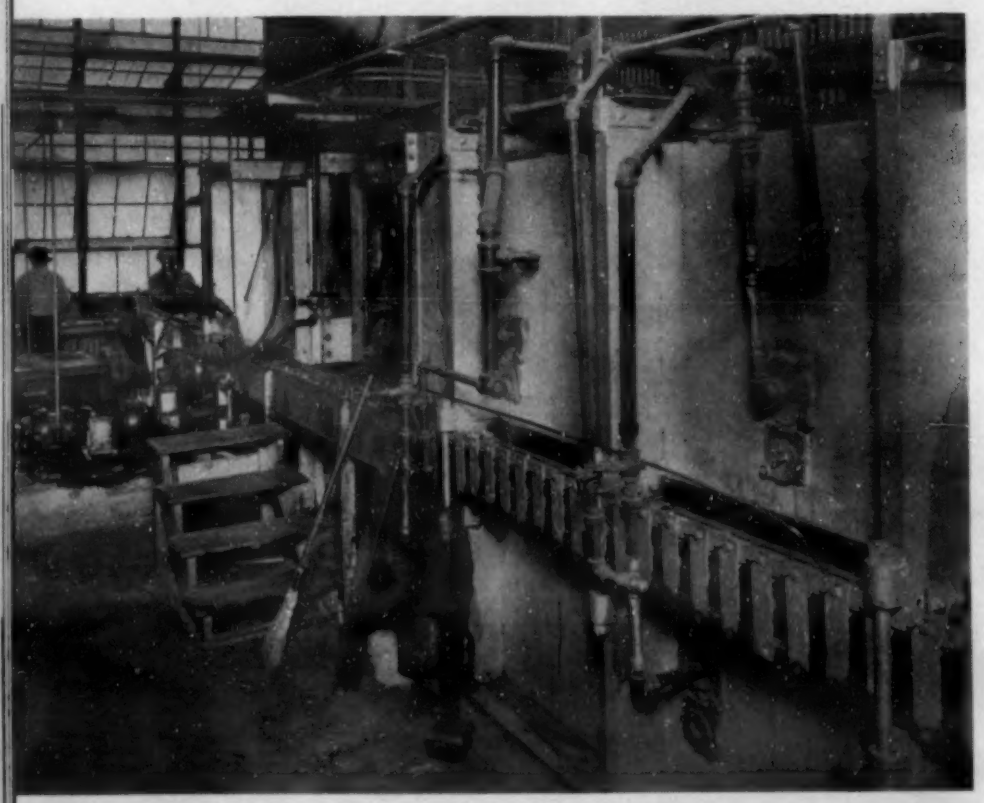
Due to their nature the Alnico alloys are cast—they cannot be machined, rolled, or drilled, and can be finished only by grinding. Both theory and experience have demonstrated that the best melting equipment for such mixtures, is the coreless induction furnace. For this purpose the Simonds company, in an up-to-date foundry department, has two 600-lb. and two 100-lb. Ajax-Northrup high frequency

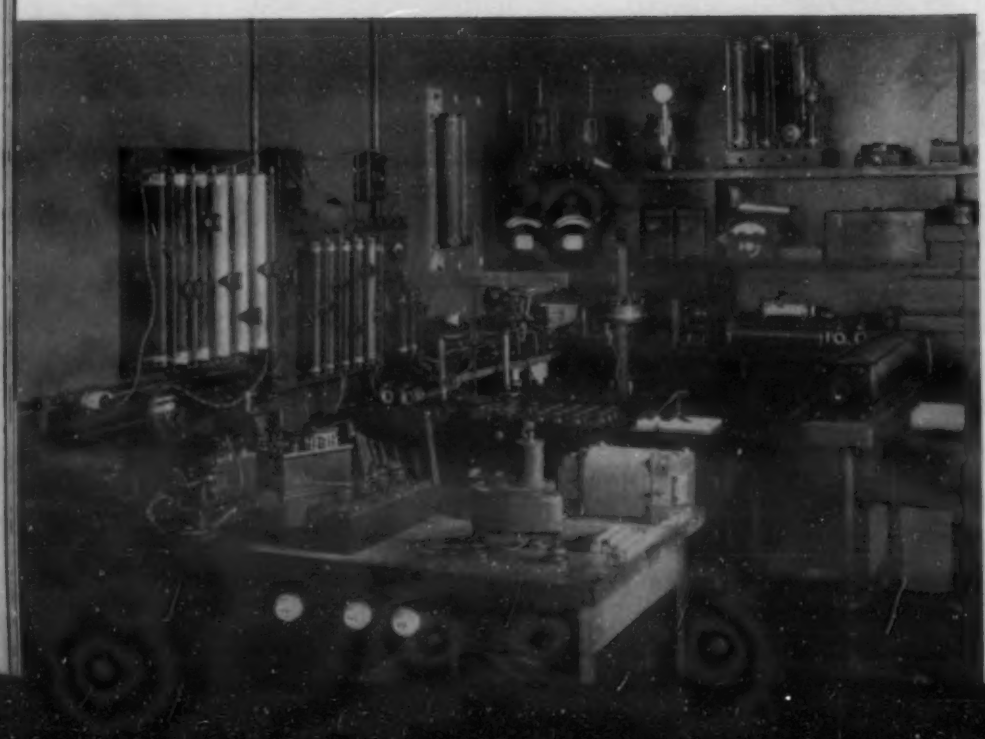
units and also one 50-lb. furnace, with the necessary motor-generator equipment. These are shown in one of the illustrations.

Composition of the Alloys

The chemical specifications for these alloys average about as follows: Alnico, 20 per cent Ni, 12 per cent Al, and 5 per cent Co, balance Fe; so-called "Alnic" (no Co), 25 per cent Ni, 12 per cent Al, and balance Fe. In these the carbon should range from 0.02 to 0.06 per cent, the silicon and manganese from 0 to 0.10 per cent each—or as low as possible and not over 0.15 per cent.

Another type of permanent magnet steel, made in these furnaces and cast, are known as cobalt magnet steel castings, containing various percentages of cobalt depending on the requirements of the magnet. These run from a minimum of 3 to a maximum of 40 per cent Co. These cobalt steels contain varying percentages of tungsten and chromium, depending on the cobalt content and the magnetic results required.





Various other grades of the Alnico type are made suited to special applications.

Besides returned scrap, the raw materials used include metallic cobalt, nickel and aluminum, all virgin grades. In selecting scrap for melting, care must be taken to keep out any that has been oxidized such as certain parts of the sprues. The temperature of the final heats ranges from 2800 to 3000 deg. F. The time required to melt a 600-lb. charge is about 40 min. with 25 min. for a 100-lb., starting from a cold charge.

Two advantages stand out in the adaptability of the Ajax high frequency furnaces for these grades of steel: No carbon pick-up and thorough mixing—thoroughly demonstrated by the experience in this foundry. The high temperature attainable is another.

These castings are made in sand molds of both dry and green sand, and molding is done on up-to-date molding machines. After the molten metal has been cast into molds and the castings are set, the molds are shaken out; the entire cast is sandblasted, after which sprues and gates are broken or cut off as may be necessary. A slight portion of the gate remaining on the casting is then ground and the castings are ready for heat treatment.

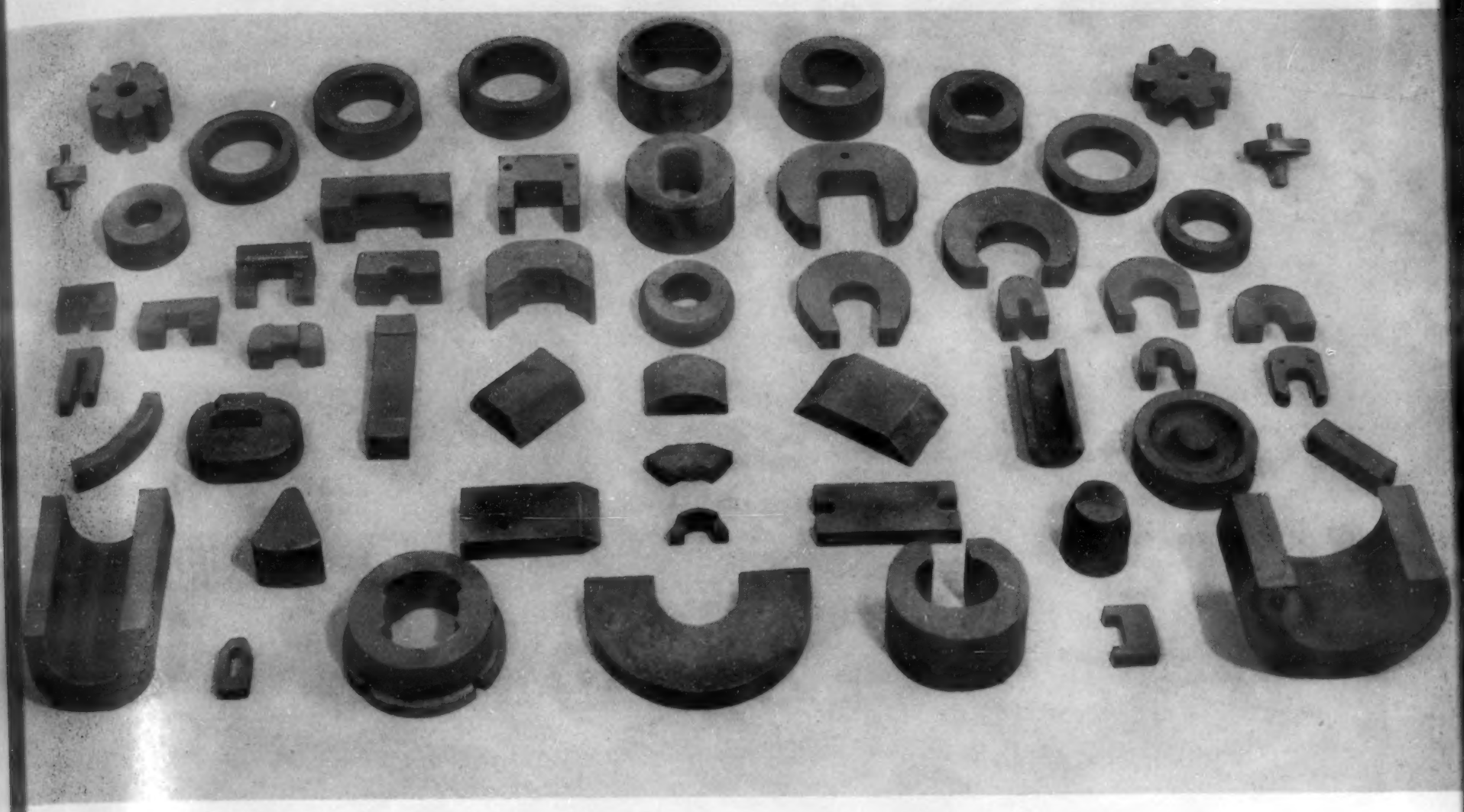
Heat Treatment

Their heat treatment is interesting and entirely different from that ordinarily given steels, including magnet steels. To secure the maximum in magnetic properties, the Alnico castings must be submitted to a definite, carefully controlled heating cycle inasmuch as Alnico is a precipitation hardening alloy. It is first heated to a high temperature for a solution treatment and from this temperature it is cooled at a definite determined rate to approximately 1300 deg. F., this rate of cooling depending entirely upon the composition of the Alnico. Most of the castings are then drawn for a short interval at 1300 deg. F. and allowed to cool in air or in some instances in the furnace.

For this purpose the company uses a continuous gas-fired furnace, built by the Salem Engineering Co., Alliance, Ohio. It contains three zones—the heating, cooling and drawing, and is under complete automatic pyrometric control. In general the heating period is from 1975 to 2100 deg. F., depending on the grade of Alnico and this requires 15 min. to 1 hr. In

Top left: A close-up view of a section of the automatically controlled continuous heat-treating furnace. A corner of the magnetic inspection bench, where all Simonds castings are individually tested, may be seen in the background.

Bottom: A section of the magnetic testing laboratory.



Alnico magnet castings of various shapes, not ground. Scale: 35/64 = 1 in.

the cooling zone the alloy is cooled to a drawing temperature which requires from a fraction of a minute to 4 to 5 min. depending on the grade and the size. The temperature here is about 1300 deg. F. From this zone the castings go to the drawing compartment where they are subjected for about 15 min. to a temperature of about 1300 deg. F. After removal from the furnace they have a hardness of 55 to 59 Rockwell C. Where castings must be cooled more quickly than the cooling zone of the continuous furnace permits, they are cooled manually with a degree of quenching from oil, as one extreme, to airblast.

In addition to the special continuous heat-treating furnace, there are two batch furnaces, gas-fired, for use on special orders.

Besides castings of definite shape for definite applications, bars of uniform cross section are also cast which in many cases are afterwards cut by the supplier into individual magnets, or by the consumer in the same manner, with a high-speed cut-off wheel for the purpose.

Magnetic Properties and Uses

A word about the magnetic properties and uses. The majority of Alnico alloys are made with balanced values of coercive force and residual magnetism in order to develop the maximum energy value. Alnico has a coercive force of 400 to 440, with a residual value between 7000 and 7500. With variations in composition, the coercive force can easily be made as high as 600 to 650, although at the expense of the residual value and also of the energy product value.

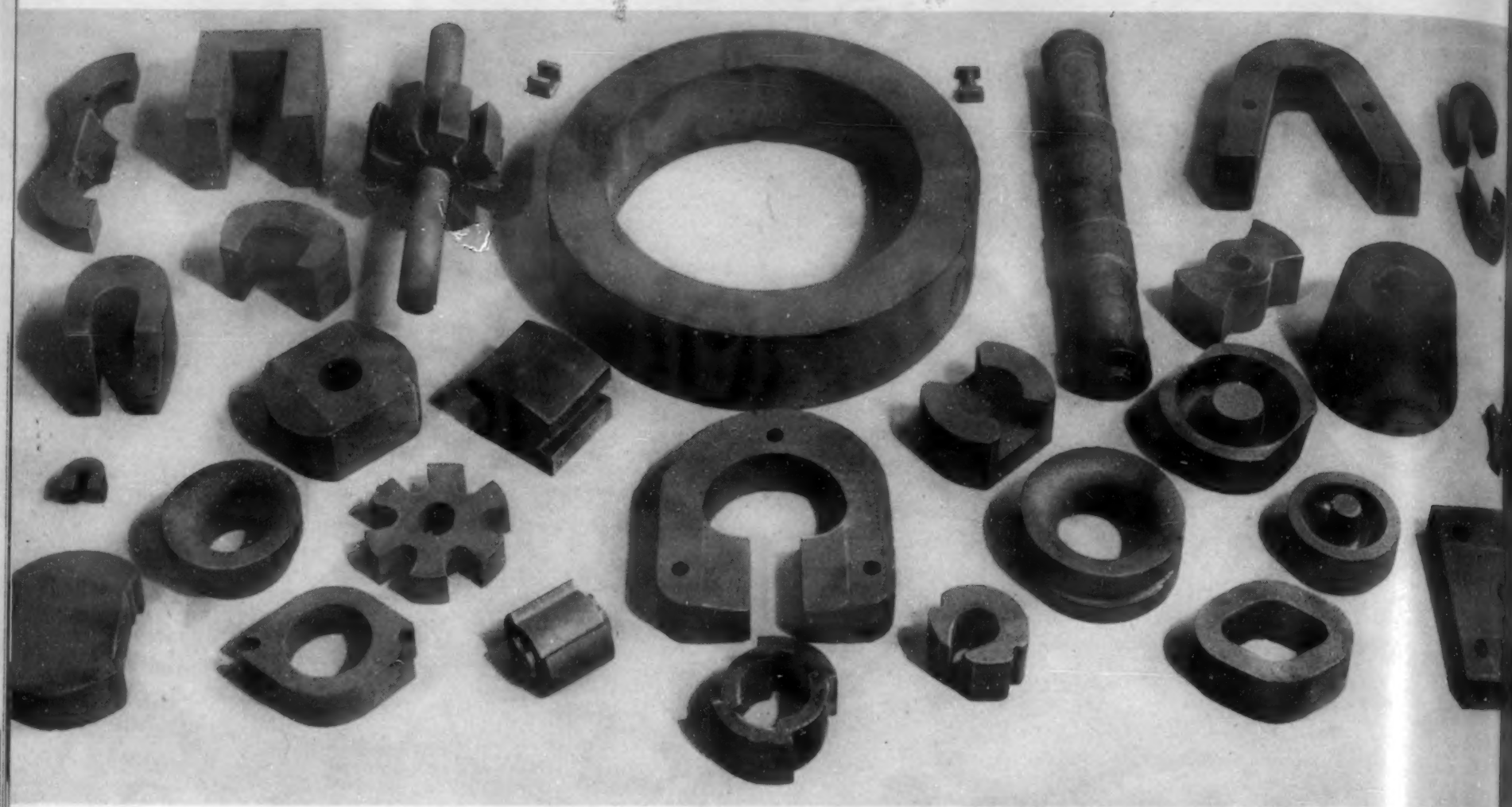
The cast cobalt (36% Co) alloy, containing W and Cr, has a coercive force of about 250 with a residual value of approximately 10,000. This alloy is machinable, differentiating it from the Alnico types. It is not regarded as a true precipitation hardening alloy.

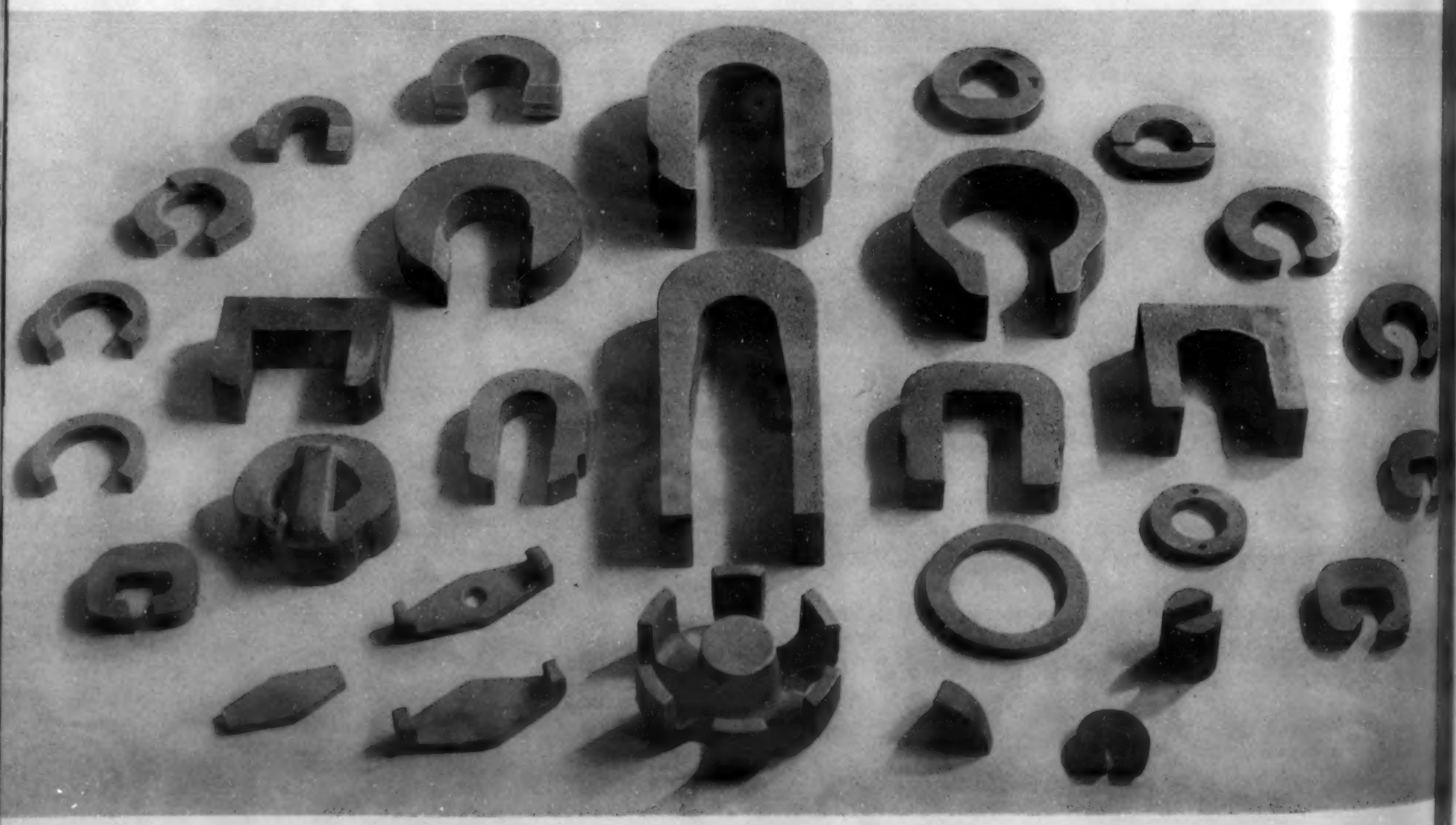
The uses to which the permanent magnets as a class are put are legion. Some of the important ones are: Loud speakers, telephone receivers, microphones, magnetos, galvanometers, generators, magnetic separators and chucks, head sets, various types of meters, relays, and so on. Development of the radio industry has increased the demand.

Outlook for New Alloys

In the same manner as the Alnico types have

Other Alnico magnet castings, not ground. Scale: 35/64 = 1 in.





Magnet castings, 36 per cent Co, not ground. Scale: 35/64 = 1 in.

proven a better product, will research in turn develop something still better? Already there has been developed an alloy by the Japanese—the new KS alloy. This is a precipitation hardening alloy which contains a very high percentage of titanium as well as high cobalt and nickel in which a small percentage of aluminum exists. This alloy, developed by Professor Honda, has a much higher energy product value than any Alnico so far made, but it has offered a great many difficulties towards successful manufacture, and if practical its price would be so high as not to interfere with the regular use of Alnico.

Since Alnico was originally found to have such high magnetic values, a great deal of effort has been expended in every country searching different combinations to develop magnetic alloys of other compositions. Very unusual magnetic materials have been made with various compositions including silver and platinum, but while the values have been unusual they are not the balanced values which make them practical for the ordinary magnet, though some of these special compositions have definite applications not commonly associated with the use of permanent magnets as we consider them.

Sintering of Copper and Tin Powders

by **H. E. HALL**

General Manager,
Metals Disintegrating Co., Inc.,
Elizabeth, N. J.

Because those engaged in the powder metallurgy industry justifiably guard their respective secrets so closely, very little new and useful factual material on this subject has as yet been published—at least in American journals. It is with much pleasure, therefore, that we present this article—a simple, remarkably clear elucidation of the structural stages in producing a porous bronze bearing from copper, tin and graphite powders. To the best of our knowledge this is the first time that colored photomicrographs have been published showing the evolution of an alloy from discrete metal particles.—The Editors.

THAT COMPLETE ALLOYING of copper and tin powders to form bronzes may be readily obtained without fusion of the constituents in the ordinary sense of metallurgical practice is generally well-known. The mechanism by which powders of copper and tin thus form alloys has been followed and is depicted in the series of colored photomicrographs (Figs. 1-6) which are the nucleus of this article.

Because chief commercial interest at present in bronzes made from powdered constituents lies in their use in the form of porous bronze bearings, compositions and technique used in this industry were employed in the work reported here. A representative bronze for this service might be one containing 84.6 per cent Cu, 9.4 per cent Sn, 6.0 per cent graphite. The graphite is added largely for mechanical reasons, and choice of powder metallurgical technique is made for the two-fold purpose of evenly distributing this graphite and for attaining the porous structure visible in all the photographs (black and out of focus areas). Porosities varying between the general limits of 0.5 to 40 per cent can thus be obtained at will with this technique. The finished bronze shown, for example, possesses a porosity of 25 per cent. This porosity is desired for the following reasons:

(a) To improve the mechanical performance of the bearing.

(b) To act as a reservoir for lubricating oil,

with which the bearing is impregnated by the manufacturer.

(c) To provide a device independent of extraneous mechanical means for continually supplying oil to the working surface. This is achieved because of the intercommunicating nature of the pores, their great number and small size. These pores thus function as a great number of capillary tubes, the oil rising therein to maintain oil contact with the working surface. It is this action that is responsible for the name by which these bearings are sometimes but erroneously known, "oil-less" bearings, instead of the precise explanatory term "self-lubricating" bearings.

Materials and Processing

The copper and tin powders used in this work were representative samples of powders of a grade extensively used by bearing manufacturers, the graphite was supplied by Acheson Graphite Corp. Pertinent characteristics of these materials are:

	Copper Powder (M.D. No. 151)	Tin Powder (M.D. No. 101)	Graphite (Acheson)
Method of preparation:	Reduction of oxides	Atomization	.....
Screen analysis:			
MESH	Per Cent	Per Cent	Per Cent
+150	Trace	Nil	0.1
−150 +200	10.2	0.8	0.8
−200 +250	4.0	(1.6	4.0)
−250 +325	15.3		
−325	70.5	97.6	95.1
Particle Size distribution as determined by microscopic count:			
MICRONS	Per Cent	Per Cent	Per Cent
0— 5	0.5	27.1	1.2
5—10	4.2	30.5	14.8
10—20	20.7	24.5	19.3
20—30	18.4	11.6	16.2
30—40	16.2	2.6	25.6
40—50	10.5	1.3	18.0
50—75	18.3	1.4	4.0
75—100	10.2	1.0	0.8
+100	1.0	Nil	0.1
Apparent Density (or loading weight)	2.50	2.90	0.30

Powders well mixed in the cited proportions were compressed at 60,000 lbs. per sq. in. to give a bearing approximately 1 in. long, ¾ in. dia. with a 3/32 in. wall. After compression the bearings were heat treated by sintering at 810 deg. C., a temperature generally held to be proper for a sintering schedule of 30 min. It may be observed in passing that this temperature is one selected for economic reasons and that completely alloyed bronzes may be obtained from powders at much lower temperatures, perhaps even those below the melting point of tin (231 deg. C.). A number of unbaked or "green" bushings were introduced into the sintering furnace and bushings were removed at various time intervals to provide a series of bushings that had been subjected to progressively increasing sintering times. The bushings were then sectioned, polished, suitably etched and typically representative fields were photographed at a magnification of 400 X on Kodachrome B film.

The Photomicrographs

The colored photomicrographs thus afford a visual record of the salient changes in the transformation of the powder mixture into the finished bearing. These changes are readily apparent in that the red of the copper and the silver-gray of the tin are seen to transform progressively into the several copper-tin phases characterized by the light gray or yellow areas, and finally to attain, as a result of interdiffusion, alpha bronze—characterized by the golden yellow color of the twinned grains. In all the micrographs, the dark gray areas dispersed throughout the metal are graphite plus porosity. Although it is not too definitely shown in the micrographs, it is nevertheless known from other considerations that this porosity increases during the sintering operation.

Some alloying is noticeable after the first minute in that the tin particles have rounded somewhat and have changed color slightly at the edges. Rapidity of the diffusion, and consequent alloying, is evident from the photomicrographs taken after 3, 7 and 15 min. sintering. Alloying is substantially complete after approximately 25 to 27 min., when diffusion is complete and homogeneous golden-colored alpha bronze is the predominant metallic constituent.

Microstructure of a Compressed Copper-Tin-Graphite Powder Mixture Sintered for Various Times at 810 Deg. C.

Fig. 1—Unsintered or "green" specimen.

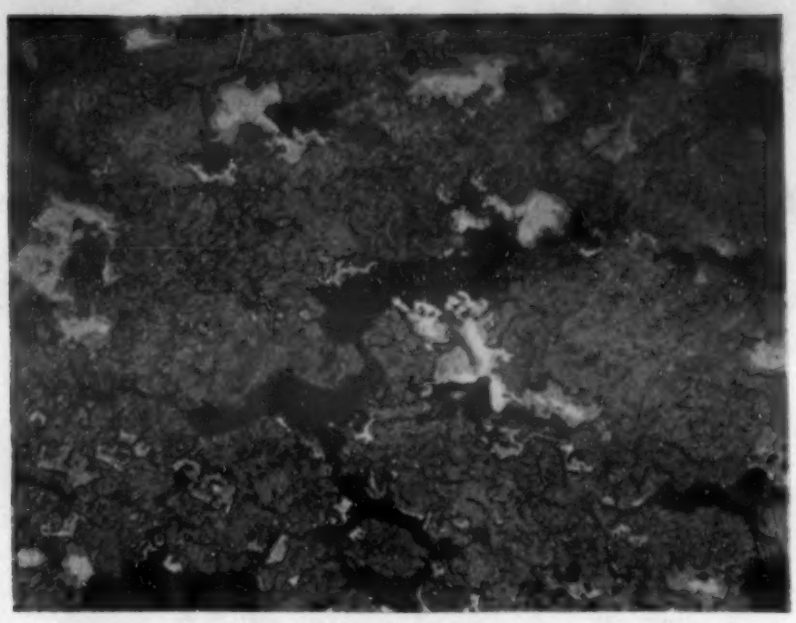


Fig. 2—Specimen heated for 1 min. at 810 deg. C.

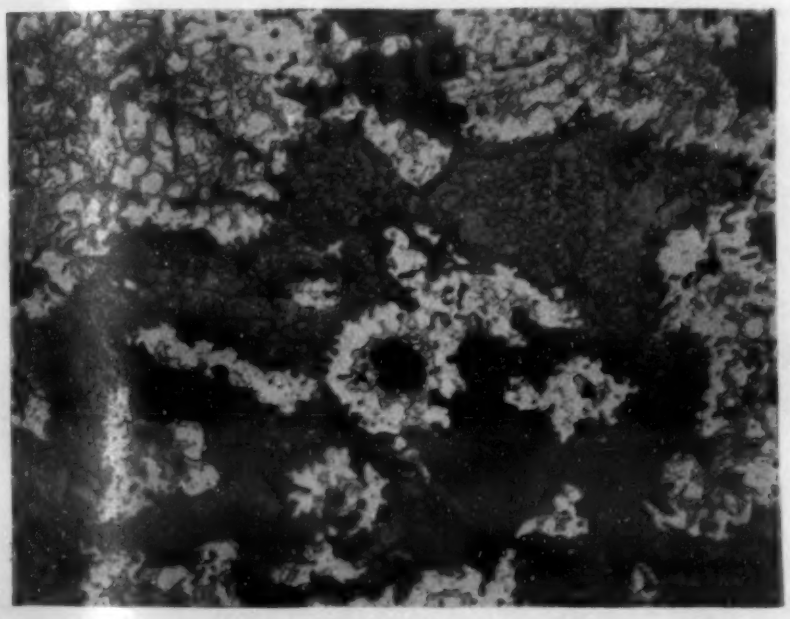


Fig. 3—Specimen heated for 3 min. at 810 deg. C.

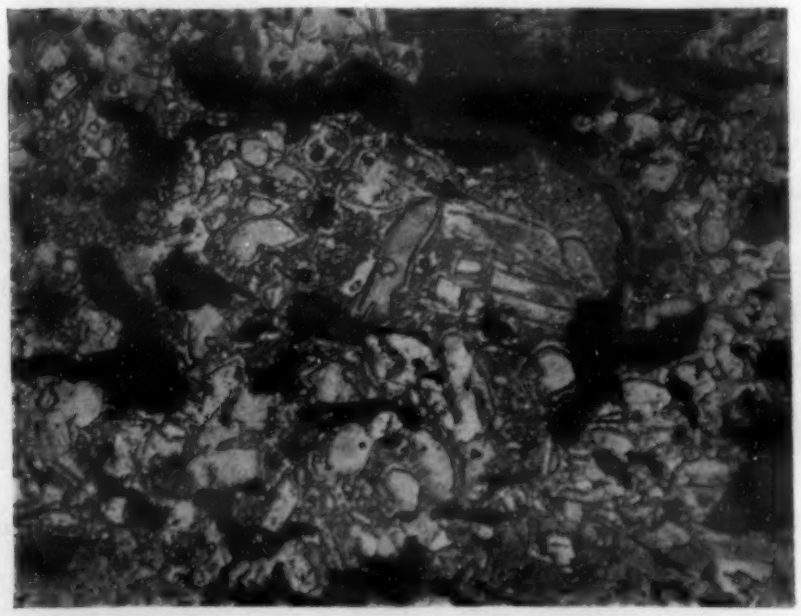


Fig. 4—Specimen heated for 7 min. at 810 deg. C.

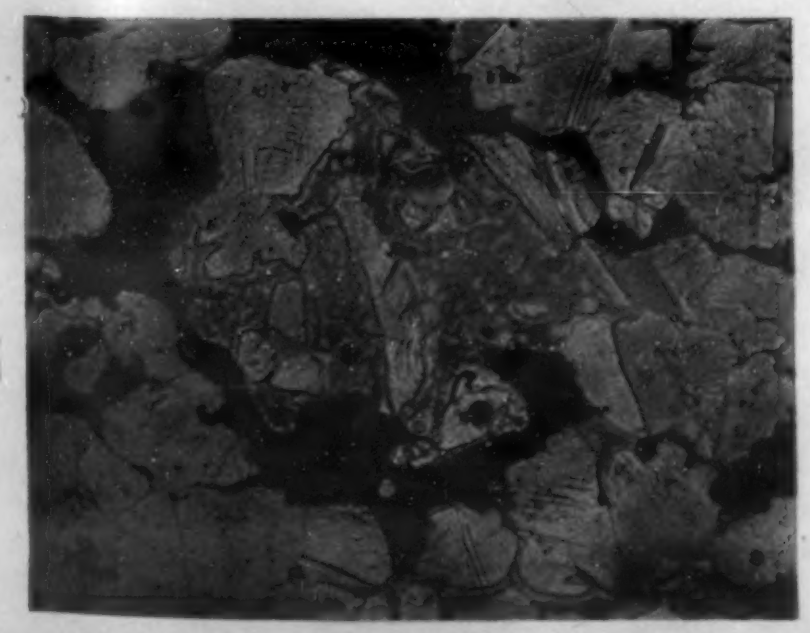


Fig. 5—Specimen heated for 15 min. at 810 deg. C.

Fig. 6—Specimen heated for 30 min. at 810 deg. C.

Photographed by S. V. Wilson, research metallurgist, Metals Disintegrating Co., Inc., on Eastman Kodachrome professional type "B" film at 400 X. Etch: Ammonium hydroxide plus hydrogen peroxide, followed by a sulphide stain.

SILVER

A PICTORIAL DESCRIPTION

Silver and Its Alloys for the Arts and Industries

TEXT AND CAPTIONS BY J. L. CHRISTIE
Assistant to Vice President, Handy & Harman, Bridgeport, Conn.

PHOTOGRAPHS BY DON GRAF
Staff Photographer, Reinhold Publishing Corp.

SILVER IS ONE OF THE FIRST METALS man discovered and put to every day use. Everyone has some knowledge of its general history and of its use as money—and who is not acquainted with the importance of its centuries old standing in the making of jewelry and silverware? But silver, like other metals, has undergone revolutionary changes in its fabrication since the turn of the century. Centralized production, under laboratory guidance, has replaced older methods, and new alloys have been developed which have decidedly broadened the use of silver, especially in the industrial field.

Today, though few may realize it, silver and its alloys are being used or are working for us practically every minute of the day. You meet it first at breakfast in knives, forks and spoons. Your food comes from a refrigerator that depends on silver brazing alloys in its freezing units. Transportation—your car, train, boat or airplane—is constantly finding more uses for the unique qualities silver gives in the form of electrical contacts or as a means of making better joints between metals at low cost. Electric elevators, motors, transformers and control equipment look to these alloys for reliable connections. Manufacturers of steam turbines, toasters, telephone systems, heat exchangers, chemical equipment, gasoline lamps and stoves, cooking utensils, tubing, valves and fittings are numbered among those who use silver and its alloys in volume. In fact, these alloys as brazing materials have, within the past seven or eight years, won wide enough acceptance so that it can now be said there are potential uses wherever ferrous or non-ferrous metals with melting points above 1200 deg. F. must be joined.

Fine silver also has many specialized uses. It is made into tubing and sheets for fabricating equipment required where corrosion is a problem and it is being welded by the atomic hydrogen and carbon arc methods, using fine silver rods. Silver clad metals also have been developed and sintered metals containing silver are finding a place in the electrical contact field.

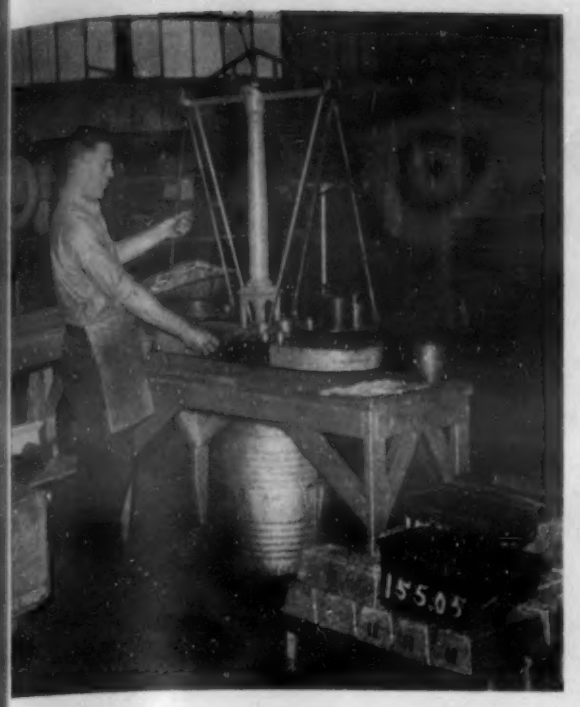
The development work and manufacturing of metals of this kind have been carried on for many years in the plant of Handy & Harman, Bridgeport, Conn. Here you find a modern silver mill turning out sheets, strip, rods and wire of silver and its alloys on a high production basis. While the detailed processes for different alloys vary, the basic principles of melting, rolling, drawing and annealing are similar. The various processes are operated under laboratory control. A centralization of production is in a high degree responsible for speeding up manufacturing processes and for many of the improvements in production which have been effected during the past quarter century. With standardized compositions and technical control this centralization has resulted in uniform products of high quality.

The pictures which follow were taken in the Handy & Harman plant and illustrate typical steps through which silver and its alloys go before final inspection releases them for shipment to the ultimate user.

1

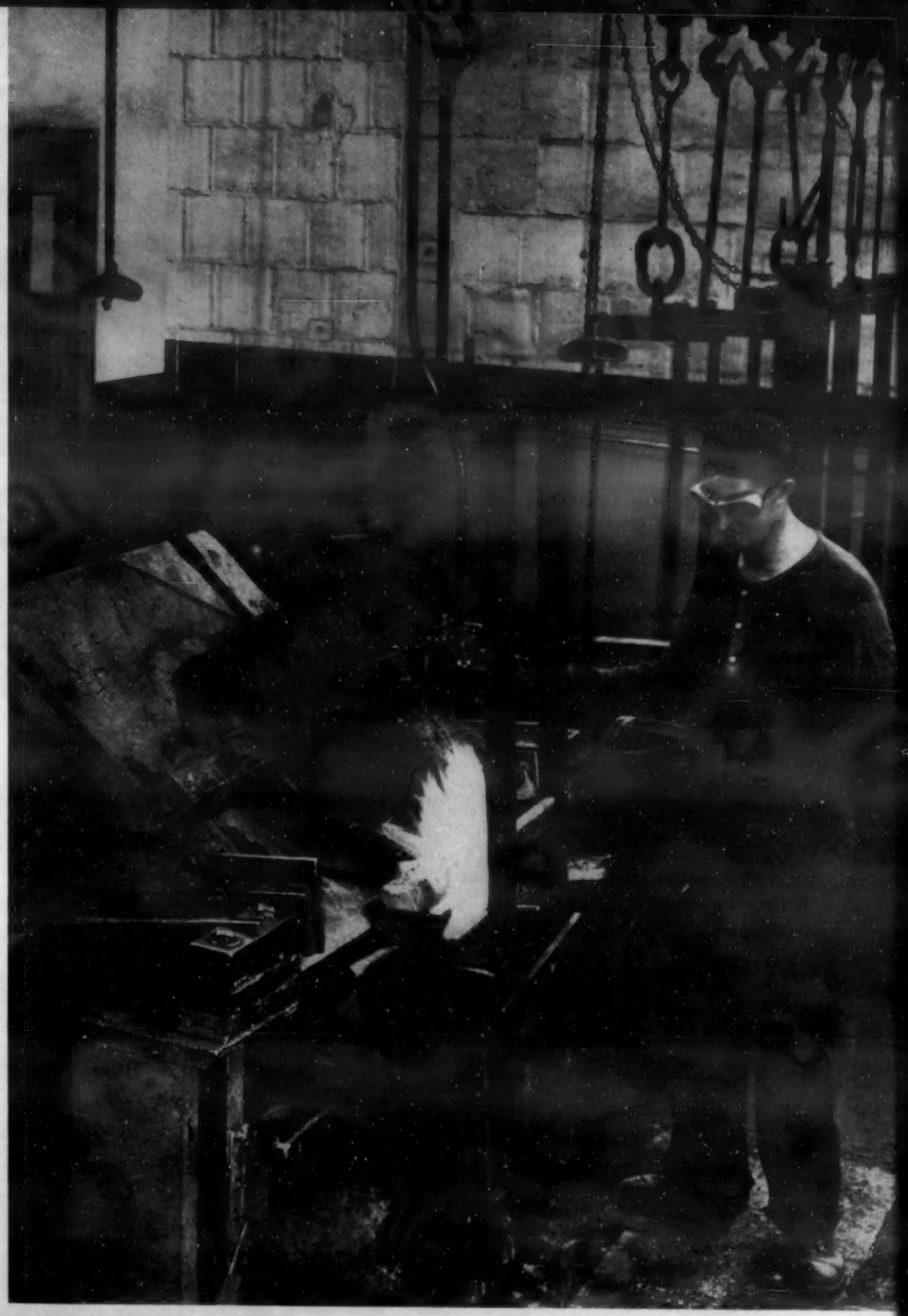
(Illustrated on preceding page)

The fine silver bars are bought in the world markets. They weigh about 1000 troy ounces (Approx. 70 avoirdupois lbs. each) and have a fineness of 999+. To the left—sterling silver bars, after passing through the break down mill and first annealing operation. They have been scalped or milled off to remove any impurities the casting skin might contain.



2 ↑

WEIGHING A MELT. *Here fine silver and the base metals required to make up a wide variety of silver alloys are accurately weighed in exact proportions and are then sent to the melting department.*



3 →

POURING A MELT. *Melts are loaded into electric induction furnaces (Ajax) having a capacity of 12,000 troy ounces. Before any melt is poured a pyrometer reading is taken to determine the exact temperature. A sample of every melt is taken and analyzed. Several other types of melting furnaces are used.*

4

THE FIRST ROLLING *or break down takes place in this heavy mill. Bars are reduced rapidly to about 1/2 in. thickness before the first anneal is necessary.*

←

5

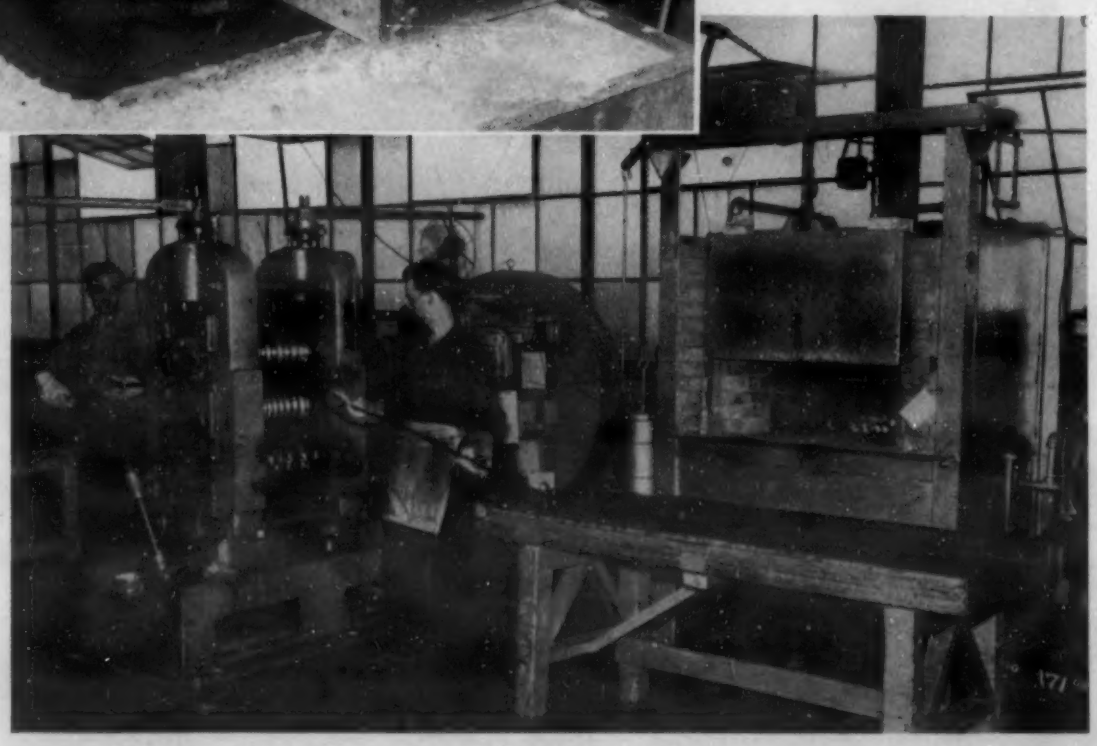
THIS WIDE SHEET *in the break down mill is nickel clad silver—50 per cent Ni and 50 per cent Ag. It is 24 in. wide and requires special rolling procedure.*

→

6

SALT BATH ANNEALING *is fast and thorough. It is used in annealing heavy bars. They are loaded in steel racks and lowered into a molten bath of salt. Bars are annealed in less than 10 mins. at a temperature of about 1200 deg. F.*

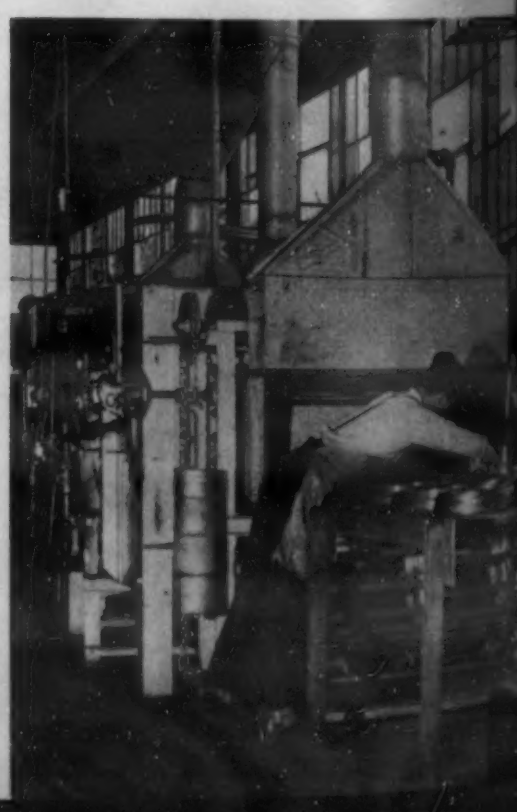
←



7

BARS FOR WIRE *or rods are broken down on this three-high roll. "Sil-Fos" and "Easy-Flo" brazing alloys, as well as other silver solders, are reduced to a standard size preparatory to further rolling or drawing.*

←



8

THE ANNEALING OF BRAZING ALLOYS *is taken care of in this Rockwell furnace at a temperature of 1050 deg. F. in a deoxidizing atmosphere. Wire, rods, sheet and strip are loaded onto a self feeding belt.*

→

9

FURTHER ROLLING—*reduces alloys in sheet form to the desired gauge. Wide sheets like the one shown are used to make large circles, squares or ovals. They are also cut into strip in fast time on slitting machines. The gage of the sheet shown is 0.050 in. and the width 16 in.*

→

10

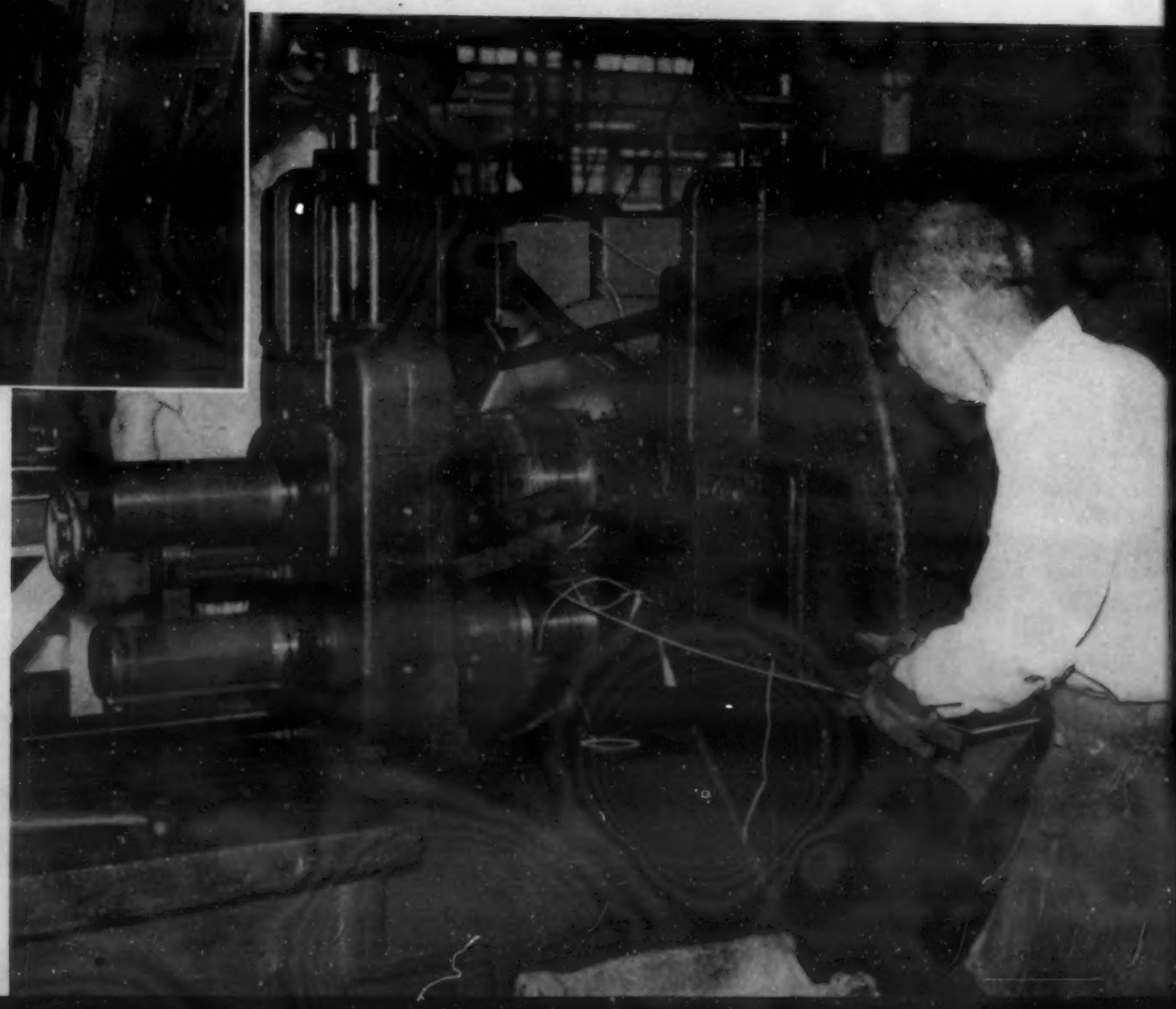
ANNEALING LONG LENGTHS *of sheet is done in coils in a water-sealed Kenworthy furnace. The atmosphere is non-oxidizing and the temperature 1150 deg. F.*

↓

11

FLAT WARE STOCK *usually about 0.075 to 0.250-in. gage, is cut to any width required on this special slitting machine.*

→



12

WIRE ROLLING *on this multiple head machine is done mostly on silver brazing alloys. The wire in one pass goes between six sets of rolls and, at the time the picture was taken, was being reduced from 0.170 to 0.115 in. The machine can be readily set for other sizes.*

←

13

FINER WIRE DRAWING *is done in the conventional way through a series of dies.*

↓

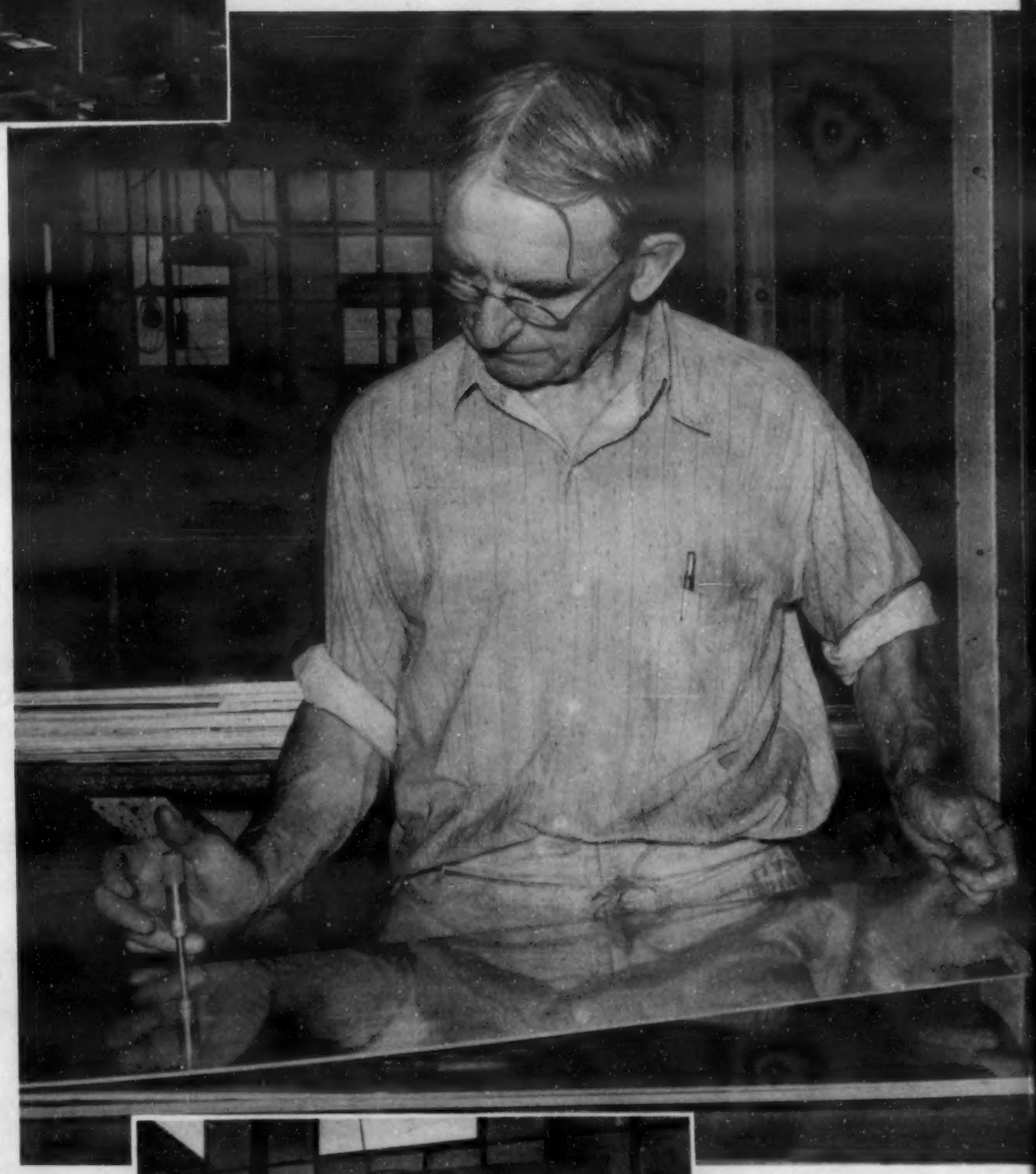
14 ↑

FINAL ANNEALING *is done in this large non-oxidizing gas atmosphere furnace. The temperature is pyrometrically controlled and is held a little under 1200 deg. F.*

15

FINAL INSPECTION *includes checking dimensions and a thorough examination of all surfaces. Also, before any metal can be shipped a laboratory report on the metal's analysis must show that its composition is correct.*

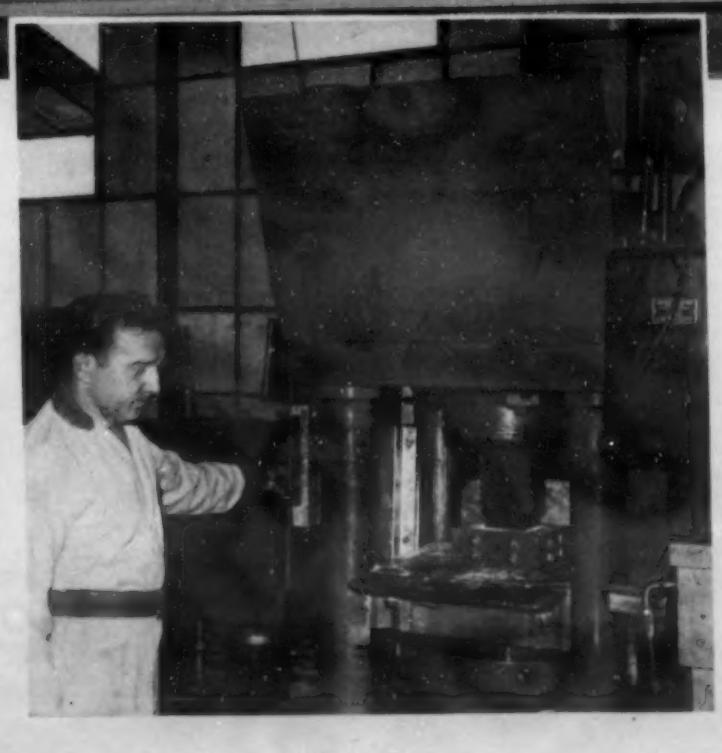
↓



17

POWDERED METALS—HOT PRESSING—*The composition here is 95 per cent silver and 5 per cent graphite. At a temperature of 1200 deg. F. and pressure of 3900 lbs. per sq. in., the powder is solidified to make a bar which can be rolled into sheets and cut to usable forms and sizes.*

↓



← **16**

POWDERED METALS—COLD PRESSING — *the composition being pressed is 70 per cent Ag. and 30 per cent Ni. The powder, thoroughly mixed, is formed in a hydraulic press under 2000 lbs. per sq. in. into a bar 3 x 4 in. and about 3/4 in. thick. This composition is made for use as electrical contacts.*

Low Lead-Silver Alloys for Bearings

Some Properties Pertinent to Their Use

By R. W. DAYTON

Metallurgist,
Battelle Memorial Institute,
Columbus, Ohio.

The author has done some excellent research on the silver-rich alloys for bearings. Suitable metals for bearing, particularly for airplane engines, is an important topic now. In our December, 1938, issue, Dr. Dayton contributed a timely discussion of these alloys.

This article is a further contribution to this subject, based on more research. In it he shows that bearings of a 3 to 4 per cent Pb-Ag alloy are highly resistant to seizure and that they have the physical properties which enable them to carry high loads without mechanical failure. He also demonstrates that the best method of bonding Pb-Ag alloys to steel is by electrodeposition.—The Editors.

ENGINE TESTS of the Pratt and Whitney Aircraft Co. and of the Allison Engineering Co. have proven that silver base alloys have great promise for use in highly stressed bearings. A laboratory investigation of a variety of silver base alloys has shown[1] that alloys of silver with less than 6 per cent of lead were most promising. These alloys have greater resistance to seizure than other silver base alloys or present standard bearing materials. It was therefore believed that if the other necessary properties of a bearing material, such as strength, corrosion resistance and bonding ability, were possessed by these lead-silver alloys, they would be excellent for heavy duty bearing service.

An investigation of some of the properties of a series of the alloys which contained about 0 to 5 per cent of lead has been made, to find whether these other properties show the lead-silver alloys to be suitable for such bearings. The results have shown that the alloys are stronger than silver, which itself is strong enough, and corrosion resistant. Bonding of the alloys to a steel back is a difficult task with usual methods. However, an excellent bond can be obtained by the methods of electrodeposition.

Preparation of Alloys

Six silver alloys containing 0 to 5 per cent lead were prepared from double refined silver (99.995% Ag) and test lead. Three hundred gram melts of each alloy were made in an Acheson graphite crucible in a gas fired furnace, using a reducing flame. Two ¾-in. diameter, 2-in. long bars were cast from each melt, in warmed graphite molds. The analyses of the melts are given in Table 1.

One ingot from each melt was tested as cast, the other was given an annealing treatment of 2 days at 570 deg. F. (299°C.) followed by 2 days at 375 deg. F. (191°C.). The higher temperature of this annealing treatment is only slightly below that of the eutectic, (579°F., 304°C.) at which temperature the solid solubility of lead in silver is a maximum (see Fig. 1) and this anneal was intended to destroy the cast structure as much as possible by dissolving the lead. The lower temperature anneal would then partially re-precipitate the lead in a different form than it was originally.

It was planned to find whether this change in structure had an influence upon the bearing properties, the corrosion resistance, or the physical properties of the alloys.

Bearing Properties

The seizure resistance of the alloys was determined in the Amsler wear tester by a previously described[1] testing procedure. This test of the material as a bearing determines the maximum load at

Table 1. Analyses of Silver-Lead Alloys

Sample	Lead Content, and by Analysis
59	0.02
60	0.98
61	1.55
62	2.96
63	3.68
64	4.68

which the test bearing can run without seizure, and it has been found that the test results are in accord with service results. Tests are made using both ground and polished shafts, and it has been found that if the seizure resistance against a ground shaft is much lower than against a polished one, the bearing metal is not a reliable one. The test results desired are therefore a high seizure resistance, equally good with either ground or polished shafts. The bearing metal then is trustworthy in seizure resistance.

The seizure pressure for each alloy is reported in terms of the per cent of that for a certain lot of a copper-lead containing 28 per cent Pb, 1 per cent Ag, balance Cu, whose seizure resistance is called 100 per cent on this arbitrary scale. This copper-lead is sufficiently seizure resistant so that it never seizes in a heavily loaded aircraft master connecting rod bearing. Therefore, if any alloy has a relative seizure resistance greater than 100 per cent, it may be assumed that it, too, will not seize in this service.

Each alloy was tested in four different conditions of heat treatment, as shown in Table 2. The results obtained against polished shafts show that lead additions do not appreciably change seizure resistance. Against ground shafts, however, it is seen that lead additions are necessary to improve the reliability of a bearing, and that about 3.50 per cent lead is required before the alloy performs as well against ground shafts as against polished ones.

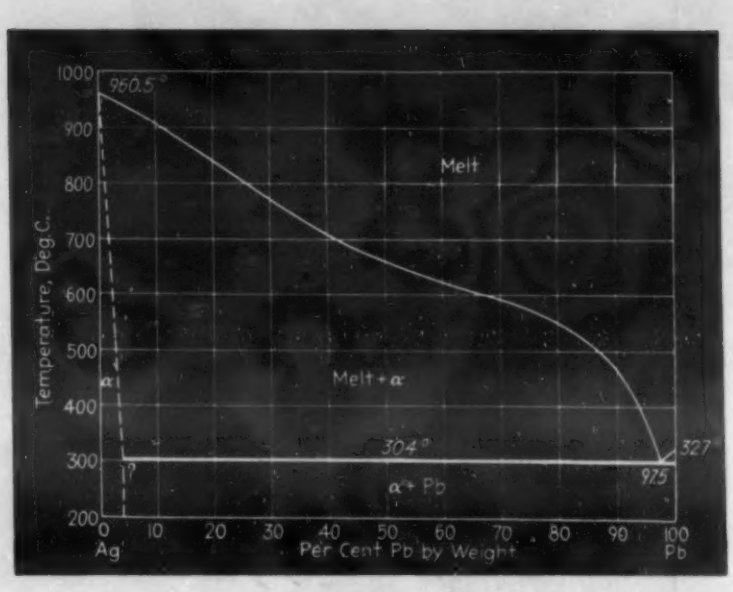


Fig. 1—Constitution diagram of silver-lead alloys, from Hansen.[3]

There is no consistent difference between the chill cast and annealed specimens. The corrosion tested specimens, however, are in every case superior to the same specimen before corrosion testing, and this is attributed to the 8-day anneal at 325 deg. F., which was a by-product of the corrosion testing.

The results show that silver-lead alloys containing more than about 3.50 per cent lead are extremely seizure resistant, nearly half again as much so as an excellent type of copper-lead. The advantages of the silver-lead alloy in an application where seizures are troublesome, are obvious.

Table 2. Relative Seizure Resistance of Silver-Lead Alloys

Spec. No.	Lead Content by Analysis, Per cent	Specimen Condition	Relative [1] Amsler Seizure Pressure [2] Polished [4] Shaft [3] Per cent	Ground [5] Shaft [3] Per cent
59	0.02	Chill Cast	110	50
		Chill Cast—Corrosion tested [6]		75
59A	0.02	Annealed [7]	125	55
		Annealed [7]—Corrosion tested		90
60	0.98	Chill Cast	125	80
		Chill Cast—Corrosion tested		105
60A	0.98	Annealed	110	80
		Annealed—Corrosion tested		105
61	1.55	Chill Cast	120	80
		Chill Cast—Corrosion tested		125
61A	1.55	Annealed	100	90
		Annealed—Corrosion tested		120
62	2.96	Chill Cast	110	85
		Chill Cast—Corrosion tested		125
62A	2.96	Annealed	115	100
		Annealed—Corrosion tested		125
63	3.68	Chill Cast	130	135
		Chill Cast—Corrosion tested		145
63A	3.68	Annealed	125	105
		Annealed—Corrosion tested		140
64	4.68	Chill Cast	130	110
		Chill Cast—Corrosion tested		140
64A	4.68	Annealed	125	135
		Annealed—Corrosion tested		140

[1] The seizure pressures obtained are compared to those obtained with a certain lot of an alloy of 28% Pb, 1% Ag, balance Cu, alloy, whose frictional properties are good enough that the loads and speeds of aircraft service can be carried without seizure.
[2] Tested at 250 deg. F., using S.A.E. 30 Mobiloil.
[3] Shafts are carburized 2512, of 57 Rockwell "C" hardness.
[4] Polished with No. 4/0 emery, then buffed with rouge.
[5] Ground with No. 0 emery.
[6] The improvement of the corrosion-tested specimens is attributed to the effect of the additional annealing, 8 days at 325 deg. F.
[7] Annealed two days at 570 deg. F., followed by two days at 375 deg. F.

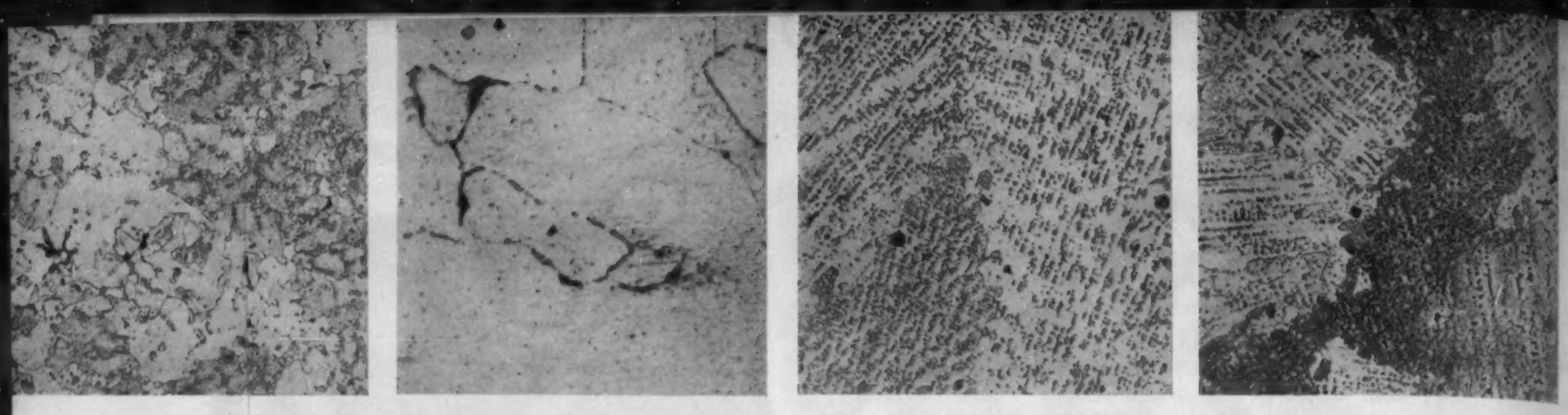


Fig. 2—Specimen 66 (approximately 4% Pb-Ag) sand cast. The details of the structure are shown in Fig. 3. 100 X. Fig. 3—Specimen 66 (approximately 4% Pb-Ag) sand cast. The distribution of lead in globules along grain boundaries and in the grains is apparent. 1000 X. Fig. 4—Specimen 63 (3.68% Pb-Ag) as chill cast. The lead is distributed between the dendrites, with very little along grain boundaries. 100 X. Fig. 5—Specimen 63A, (3.68% Pb-Ag). The specimen was chill cast then annealed 2 days at 570 deg. F., 2 days at 375 deg. F., 8 days at 325 deg. F. There is very little change due to the annealing, only slightly more diffuse dendritic traces. 100 X.

Corrosion Resistance

Under certain conditions, copper-lead alloys and cadmium base alloys will fail in bearing service by corrosion. Compounds which are corrosive to the lead and to the cadmium develop in the oil after extended periods of use, and portions of the bearing metal lining are eaten away. Since a lack of corrosion resistance is a serious defect in a bearing material, the silver-leads were tested for this property.

An oil bath, containing 3 qts. of a highly refined base stock, of a viscosity of 120 S.S.U. at 210 deg. F., to which 1 per cent of oleic acid had been added, was used at 325 ± 5 deg. F. as the corroding medium. Air was bubbled through the oil at the rate of 25 to 50 cc. per min. The specimens, which were those used for the bearing tests, were left in their holders, submerged in the oil bath, and rotated so that the face used for the bearing tests traveled through the oil at a speed of about 100 ft. per min. The test was run for 8 days.

There was no corrosive attack on any of the twelve specimens during this time. The mirrorlike running surface of the specimens retained its high polish. It was known that the oil bath was corrosive, since a strip of lead immersed in it for a portion of the test period was badly attacked.

The specimens were seizure tested against ground shafts after corrosion testing, since by this means, it could be found whether or not lead had been removed from their surfaces. If it had, their seizure resistance would be lower than before corrosion. Since the bearing properties of all the alloys improved, it was quite apparent that the treatment in the corrosive oil had had no deleterious effects.

Physical Properties

Bearings in service sometimes fail by fatigue cracking. Pure silver bearings are not subject to this type of failure, so three types of physical tests were applied to the silver-lead alloys, to find whether lead additions weakened or strengthened silver. Since it was found that the strength of the silver-lead alloys was greater than that of the pure silver, it may be assumed that there is no danger of fatigue cracking of silver-lead bearings. The data from the physical tests are given in Table 3.

The Brinell hardness increased from 24 to 25 for pure silver to 33 to 34 for 3 per cent Pb-Ag. More lead did not give further hardening.

The strength of the specimens in ½-in. bars was measured in double shear. The shear strength was a maximum with about 1.50 per cent lead in the alloy, and did not drop much with further additions of lead.

The specimens were also tested in a repeated blow pounding test machine of the type developed by the Bureau of Standards.[2] In this machine, the specimens are supported on an anvil, and struck repeated blows by a 7.15-lb. hammer falling 2 in. The specimens used were ½ in. in diameter and ½ in. long. The whole specimen assembly was enclosed in a furnace heated so that the specimen temperature was maintained at 300 deg. F. This test is supposed to simulate the pounding of bearing service and has the advantage of being made at bearing operating temperatures.

This test too shows silver to be hardened by lead additions, up to about 3 per cent. The results at 1000 blows are quite erratic, those at 100 blows fairly uniform.

Structure

The constitution diagram of silver-lead alloys, selected by Hansen[3] as the most accurate one available, is shown in Fig. 1. It is a eutectic diagram with appreciable solid solubility of lead in silver. The extent of this solid solubility is not known accurately, but is reported to be about 4 to 5 per cent at the eutectic temperature. The physical property tests of the work reported here seem to indicate that this solubility drops to about 1.50 to 2.50 per cent Pb at 375 deg. F. (191°C.).

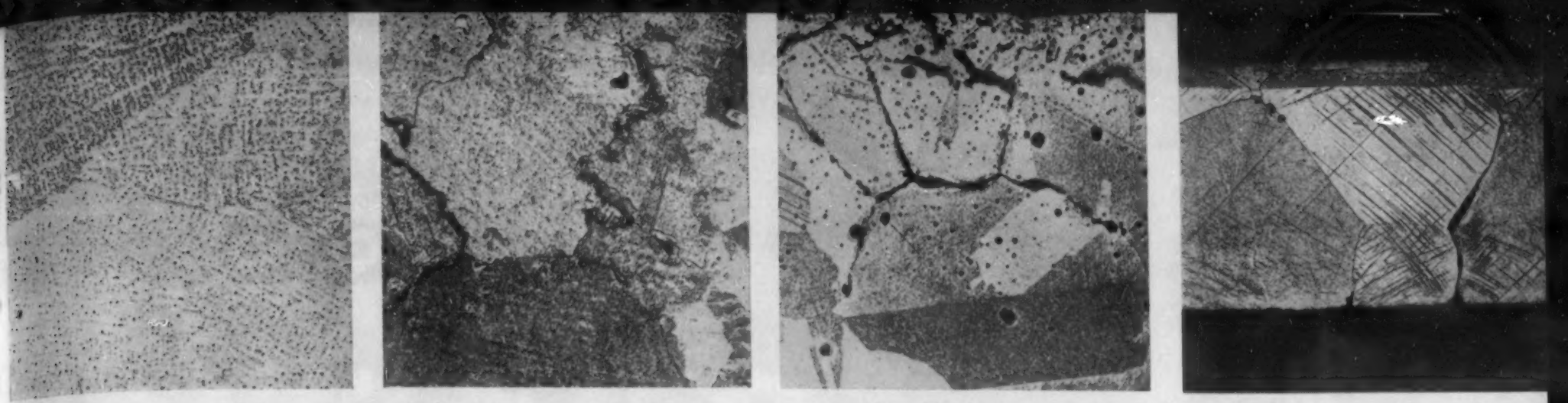


Fig. 6—Specimen 64. (4.68% Pb-Ag) as chill cast. The lead is distributed among the interdendritic fillings, and along grain boundaries. 100 X. Fig. 7—Specimen 64A, (4.68% Pb-Ag). The specimen was chill cast, then annealed 2 days at 570 deg. F., 2 days at 375 deg. F., 8 days at 325 deg. F. The lead along grain boundaries has caused numerous intergranular cracks. The dendritic traces are slightly less apparent than before, indicating some diffusion of lead. 100 X. Fig. 8—Pure silver specimen plated with 0.001 in. Pb, then heated to 1540 deg. F. (840°C.) for 1 hr., then air cooled. Intergranular cracks are very apparent. 100 X. Fig. 9—Silver bearing section plated at top with 0.00015 in. of lead, heated in a reducing atmosphere to 1500 deg. F. (820° C.) for 1 hr., cooled in air. Intergranular cracking is very apparent. The bond of silver to steel was completely destroyed. The strain lines in the crystals are due to mounting the specimen in a holder for metallographic examination, 100 X.

The typical structure of silver-lead alloys is shown in Figs. 2 and 3. A sand cast alloy containing about 4 per cent Pb was used for these two photomicrographs. In Fig. 2, taken at a low magnification, the interdendritic traces which are seen are due to the lead. In Fig. 3, lead is seen to be present along grain boundaries as well as within the grains.

Fig. 4 shows the structure of a chill cast alloy of 3.68 per cent Pb-Ag, Fig. 5 the same alloy after a low temperature anneal. There is little change due to the anneal, just a slightly greater diffuseness of the structure. When more lead is present in the alloy, however, the situation is considerably different. Fig. 6 shows an alloy containing 4.68 per cent Pb, as chill cast. This structure greatly resembles that of Fig. 4. However, upon annealing this higher lead alloy, a large number of cracks appear along grain boundaries, such as are seen in Fig. 7.

These cracks are formed during the high temperature anneal. At this temperature (only a few degrees below the melting point of the eutectic), the eutectic is extremely weak, so that when any of it is present along grain boundaries, the weight of the ingot is apparently sufficient to cause its failure thus opening up the intergranular cracks which are seen. Since no intergranular cracks appear in the 3.68 per cent Pb alloy, it is believed that only when the lead content exceeds this amount does segregation of lead to grain boundaries occur.

Lining Methods

Most bearings for heavy duty service consist of a thin shell of a bearing material bonded to a steel back. This combination possesses greater strength

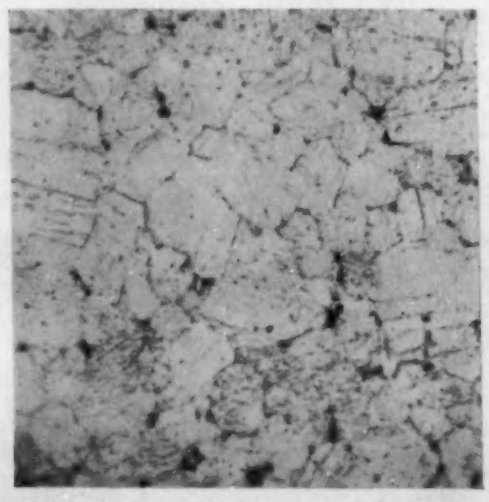


Fig. 10—Electrodeposited alloy of 3.3% Pb-Ag, heated 1 hr. at 550 deg. F. Vickers Pyramid hardness is 45. The plate is very ductile and tough under repeated bending. 1000 X.

Table 3. Physical Properties of Silver-Lead Alloys

Spec. No.	Lead Content by Analysis, Per cent	Specimen Condition	Brinell Hardness, 1/8 in./100 kg./30 sec.	Shear Strength, lb. per sq. in.	Deformation, in Per Cent in Repeated Blow-pounding Test [1] at 300 deg. F., After Following No. of Blows		
					10	100	1000
59	0.02	Chill Cast	24	13,700	6.4	13.3	28.0
59A	0.02	Annealed [2]	25	12,600	6.9	12.4	15.2
60	0.98	Chill Cast	29	14,600	5.9	10.4	15.2
60A	0.98	Annealed	29	14,600	5.5	10.8	19.6
61	1.55	Chill Cast	31	15,300	5.1	8.9	13.6
61A	1.55	Annealed	31	15,100	5.1	9.0	11.6
62	2.96	Chill Cast	34	14,500	4.4	9.2	16.3
62A	2.96	Annealed	33	14,800	4.8	8.1	9.3
63	3.68	Chill Cast	32	.....	4.6	8.4	9.5
63A	3.68	Annealed	31	14,400	4.1	7.8	11.4
64	4.68	Chill Cast	34	14,500	3.6	8.1	11.2
64A	4.68	Annealed	31	14,700	4.8	7.8	13.2

[1] Struck repeated blows at a rate of about 50 per min., by a 7.15-lb. hammer falling 2 in.
[2] Annealed 2 days at 570 deg. F., followed by 2 days at 375 deg. F.

and rigidity than a solid bearing would. Because of cost considerations, such a procedure is even more necessary with silver-lead bearings than with most other types. A brief discussion of the various bonding methods, as applied to silver-lead alloys, follows:

Thermal: Pure silver bearings are produced commercially by pouring molten silver into a clean, rotating, steel shell, then slowly cooling the assembly. A very firm bond of silver to steel is obtained. This same method has been tried for the bonding of silver-lead alloys to steel, but without success. The bond obtained has been too weak.

Diffusion: The diffusion of lead into a silver bearing, so that the running face of the bearing would be a silver-lead alloy, was thought to offer promise, but the trials which have been made have proven otherwise.

Two experiments, on heating lead plated specimens at high temperatures, (about 1500°F.) showed that at these temperatures lead first melts with silver to form the eutectic, which then penetrates along grain boundaries, thus giving rise to the undesirable intergranular brittleness. In one case, when a silver bearing was used, this intergranular brittleness was found to be present clear back at the bond line, so that the bond was entirely destroyed. Figs. 8 and 9 show sections of these bearings after diffusion.

Experiments at temperatures below the eutectic have shown that diffusion at these temperatures is entirely too slow to be practical. A lead plated specimen was heated to 550 deg. F. for 134 hrs., then the surface layers were analyzed. It was found that the 0.001-in. layer on the surface contained only 0.81 per cent Pb, so that, in order for sufficient diffusion to occur for a specimen to have a surface a few thousandths of an inch thick with a concentration of over 3 per cent Pb, several months of annealing would be required. Evidently, then diffusion is not a practical means of preparing silver-lead bearings.

Electrodeposition: One method of obtaining well bonded bearings of silver-lead on steel is the co-deposition of silver and lead by electrolysis. It has proven possible to obtain alloys of the desired composition, whose bearing properties are as good as those thermally prepared, which are extremely adherent. Due to the structure of these alloys, as shown in Fig. 10, it is expected that their physical properties will be better than those of the cast alloys, because of their lack of dendritism.

The electroplating bath used is a silver cyanide bath containing lead as acetate. Work reported elsewhere[4] has defined the plating conditions necessary to obtain the best type of deposit for bearing service.

Conclusions

Bearings made of a 3 to 4 per cent Pb-Ag alloy are extremely seizure resistant, and have the necessary physical properties to enable them to carry high loads without mechanical failure. The best method of bonding lead-silver alloys to steel is by electrodeposition.

The work here reported on is sponsored by a group of leading American silver producers, and their permission to publish the results is greatly appreciated. The assistance and advice of E. A. Ryder of the Pratt & Whitney Aircraft Co., and of G. A. Zink, of the Allison Engineering Co., have been very valuable, and are thankfully acknowledged. The co-operation of Dr. H. W. Gillett of the Battelle staff in the planning of the work and in the interpretation of the results is thankfully recognized. The electrodeposited specimens were prepared by Dr. C. L. Faust, also of the Battelle staff. Thanks are due him and others of the staff for their help and advice.

References

[1] Dayton: "The Possibilities of Silver-Rich Alloys as Bearing Materials," METALS AND ALLOYS, Vol. 9, December, 1938, p. 323-328.

[2] French, Rosenberg, Harbaugh and Cross: "Wear and Mechanical Properties of Railroad Bearing Bronzes at Different Temperatures," *Bureau of Standards Journal Res.*, p. 1,343 (1928).

[3] Hansen: "Der Aufbau der Zweistofflegierungen," p. 46, Berlin, 1936. Julius Springer.

[4] Faust and Thomas: "Electrodeposition of Silver-Lead Alloys for Bearings." The Electrochemical Society. Presented at the April 28, 1939, meeting. Preprint No. 18.

For Supplementary Note to this Article See Page 324

Role of Nickel in the Machine Tool Industry---Part 2

—Concluded from September

BY J. W. SANDS AND D. A. NEMSER

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In the October issue, the authors of this article discussed the various alloy cast irons now being used in the construction of machine tools. Not only nickel cast irons, but also chromium, molybdenum and vanadium alloy irons were included.

In this, the concluding part, the authors—both intimately associated with the machine tool industry —review the present status of nickel, chromium, molybdenum and vanadium alloy steels, and also of bronzes in the machine tool industry.

The references were published with the first installment.—The Editors.

STEELS

Much the same considerations which dictated such marked recent improvements in the cast iron components of machine tools were responsible for a more careful selection of other construction materials as well, particularly steels. Reduction of permissible tolerances, great increases in speed to handle cemented carbide tools, and the production machining of steels of such hardness and toughness as to be considered unmachinable a few years ago have rapidly consigned much ordinary plain carbon steel to the discard in favor of high grade alloy steels tailored to the particular service requirements of individual parts.

Nickel alloy steels can be made stronger, tougher, more resistant to fatigue and shock and more wear resistant than plain carbon steels. In fact about the only useful mechanical property which cannot be improved by this means is stiffness. Modulus of elasticity cannot be altered by alloying or by heat treatment.

As in the case of cast irons, the properties required of the finished part do not entirely dictate the choice of composition. The handling characteristics in fabrication and heat treatment are also of vital importance. Except in cases of severe service where only the highest grade heavily alloyed steels can be used regardless of the cost of manufacture, it is usually true that the designer has a choice of a number of steels, any of which is capable of satisfactory performance. His selection must therefore be based on the weight which he assigns to such factors as machinability, response to heat treatment, degree of uniformity from heat to heat, relative availability, warping and distortion tendency, and, usually of the least importance, first cost. Often the answer is a steel inherently superior to the service requirements but nevertheless more economical by reason of greater ease of handling.

Effects of Nickel on Steel

Nickel is completely soluble in the ferrite constituent of steel which it strengthens and toughens without loss of ductility. Not being a carbide former, its effect is independent of the carbon content of the steel and it is therefore equally as beneficial to low carbon steels as to those of higher carbon content. In steel manufacture nickel is very easy to control since it is non-oxidizing and therefore almost completely recoverable. For this reason nickel steels as a class are inherently cleaner and more uniform than steels alloyed with elements which are not so tractable. Furthermore, as nickel is used in generally higher percentages than most other alloying elements, small composition variations are not particularly influential, with the result that the nickel alloy steels are remarkably uniform in the response to heat treatment of different lots of steel of the same nominal composition. This fact is of great importance in facilitating the quantity production of duplicate parts without the necessity of readjusting the heat treatment schedule for each batch of material.

Nickel lowers the critical temperature of steel, permitting certain heat-treating operations to be carried out at lower temperatures. Nickel also reduces the minimum cooling rate required for the development of full hardness on quenching, so that most nickel steels may be oil quenched, thus avoiding the necessity for a drastic water or brine quench. These factors tend to minimize scaling, warping, distortion, quench cracks, quenching stresses and other heat-treating hazards. The lower cooling velocity required also promotes depth hardening and facilitates

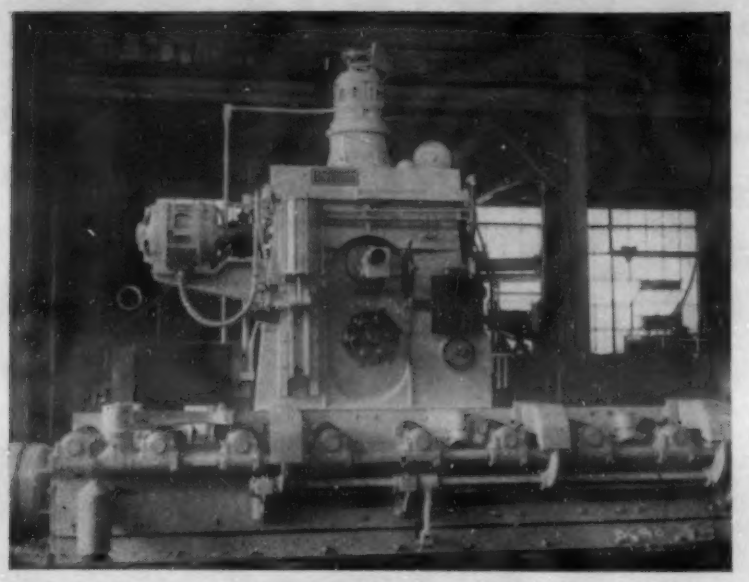


Fig. 13. Bonnot-Lentz "Billeteer" for surface conditioning billets by milling all over in place of hand chipping. This machine will handle billets up to 13 ft. long and 14 in. square. Vital steel parts such as the cutter head, arbor, shafting, arbor journals, tool holders, cap screws, feed racks, gears, elevating screws, roll table, conveying rolls and roller bearings are made of nickel alloy steels. The motor drives through a train of nickel alloy steel gears including a case hardened nickel steel worm working against a nickel bronze worm wheel. (Courtesy: Steel Equipment Division, The Bonnot Co.)

the heat treatment of parts of heavy section.

Since the influence of nickel is independent of carbon content, the element is well suited for case hardening steels which, after carburizing, possess regions of variable carbon content. Nickel strengthens and toughens both the case and core, improves wear resistance and minimizes cracking and spalling tendencies. The same heat-treating and depth hardening advantages as mentioned above are developed plus satisfactory rsponse to single quenching treatments whereby both case and core are refined at the same time without the necessity of a separate quench to take care of each in turn. In fact the resistance of the nickel steels to grain growth under the influence of long holding times at high temperatures is so great that many of them can be satisfactorily quenched directly from the carburizing heat. When this process is to be employed, it is well to use steel purchased under a fine grain size specification, such as 5 to 8 on the McQuaid-Ehn scale.

As in the case of cast iron, nickel additions to steel are frequently supplemented by other alloying elements including one or more of the elements chromium, molybdenum and vanadium. In such complex steels nickel appears to accentuate the beneficial effects of the other elements, resulting in an even greater improvement than would be predicted by the purely additive effects of the individual components.

Machine Tool Applications of Nickel Alloy Steels

A wide variety of nickel alloy steels are in present day use by the American machine tool industry by reason of the number and differing requirements of the various parts. Even parts of the same type may require widely different steels by reason of variation in size and service conditions. Gears, for example, may be of three types: (a) Gears hardened before machining; (b) gears direct hardened after machining; and (c) case hardened gears.

Gears not heat treated subsequently to machining are usually fabricated from preheat-treated bar stock or forgings. Steels with carbon limited to about 0.40 per cent are usually used since hardness is more or less limited by the machinability factor to a Brinell range of 200 to 300, although certain nickel-chromium-molybdenum steels are regularly being production machined at considerably higher hardnesses. (See Fig. 2). Although many gears of this type are still employed, improvement in heat-treating technique and the development of new steels with greater inherent resistance to warping and distortion are responsible for an increasing tendency toward the use of gears heat treated after machining. The use of this method in connection with nickel alloy gear steels permits maximum hardness and wear resistance on the teeth together with sufficient strength, ductility and toughness to insure against tooth breakage from clashing of the gears, stalling, sudden impact loads or failure due to vibration or fatigue. Such gears may contain carbon up to 0.50 per cent and, depending on the service, are hardened to Rockwell C of 45 to 55 (Brinell 440 to 550). Often, the heating for quenching is carried out in a cyanide bath to provide a superficial skin of high carbon material which improves wear resistance noticeably.

Many large gears are currently hardened on the tooth surface by the flame hardening process. A number of nickel steels are used for gears of this type, particularly nickel-molybdenum steel S.A.E. 4640 or 4650 which has been adopted by several manufacturers. Although flame hardening is usually carried out with a water quench, some concerns have substituted an air-blast quench with 4640. Despite a rather low Brinell hardness as heat treated, the tooth surface is said to work harden rapidly in service to a sort of glazed finish which provides a wear resistance comparable to that of case hardened steel.

When gears are so proportioned that tooth pressures exceed about 160,000 lbs. per sq. in., the use of a case hardened steel is desirable since the surface fatigue resistance of the best direct hardened gear will not be adequate to prevent early failure through deterioration of the tooth surface. Nearly all of the regular S.A.E. nickel alloy carburizing steels are used

depending on size and severity of service. The higher alloy grades such as S.A.E. 3312 and 2515 are without doubt the best case hardening steels at present available and are used whenever the ultimate in gear performance is required. With these steels unit tooth pressures may be as high as 215,000 lbs. per sq. in.

In addition to the medium carbon direct hardened and the low carbon case hardened nickel alloy steels some applications such as rolls, levers, small cams, etc., for which it is desirable to use direct hardening steels yielding Rockwell hardnesses of C 58 and above, require the use of nickel alloy steels with carbon in the 0.70 per cent range. Nickel steels retain a relatively high degree of toughness and ductility at these very high hardness levels at which unalloyed steels would be hopelessly brittle.

Space will not permit a detailed discussion of the many machine tool parts for which nickel alloy steels of various alloy and carbon contents are used. However, in Table II there are given some representative examples of the nickel alloy steels now most commonly usd for the components listed. The properties of these steels can be varied so widely by heat treatment that no attempt will be made to furnish detailed mechanical property data, especially since this information is readily available from the numerous mechanical property charts which have been published.[2]

Bronzes

The third important application for nickel in the machine tool field is as an alloying element in bronzes. As with iron and steel, the influence of nickel in these non-ferrous alloys is a double-barrelled effect, improving both the properties of the finished part and facilitating its handling in manufacture.

Nickel increases the strength properties of most of the common bronzes, both in tension and compression, being particularly effective in raising the elastic properties, i.e., proportional limit and yield point. Tensile strength and hardness are also increased, but to a lesser degree. This improvement is obtained at no sacrifice of ductility. On the contrary, toughness is usually enhanced and resistance to sudden shock, as measured by the Izod test, may be increased as much as 25 to 50 per cent. The data shown in Fig. 14, illustrating the effect of nickel on a sand cast 11 per cent tin gear bronze, are representative.

Nickel is effective in increasing fluidity in casting mixtures, sometimes as much as 40 per cent with a nickel addition as low as 0.5 per cent. Fewer misruns and a widened casting range result from this characteristic. Nickel also reduces the tendency toward formation of inter-crystalline shrinkage pores, an action evidenced by increased density, improved fracture and—with hydraulic mixtures—increase in pressure tightness and reduction in number of "leakers." The grain refinement secured by small percentages of nickel in sand castings within the normal pouring temperature range is from 40 to 50 per cent, as indicated by the decrease in average grain diameter. Typical applications of nickel bronzes in the machine tool industry are listed in Table III.

A chill cast 11 per cent tin bronze with about 0.15 per cent phosphorus and 1.5 per cent nickel is frequently used for gears, particularly worm wheels, and is the standard worm wheel composition of a large number of gear manufacturers. Besides

Fig. 14. Typical of the modifications in the properties of bronzes effected by nickel are the data in these charts referring to a bronze containing 11 per cent tin, 0.03 phosphorus, balance copper.

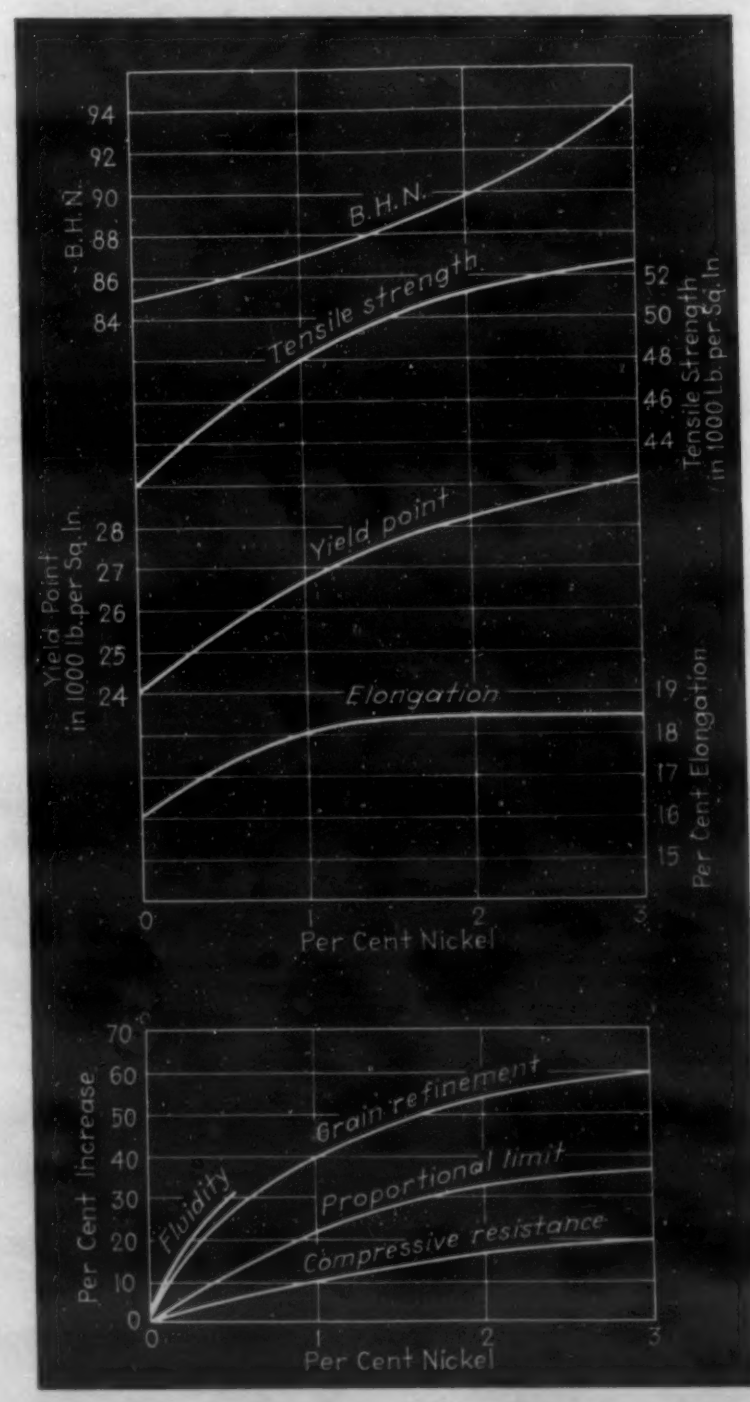


Fig. 15. Cast nickel bronze worm wheel working against a case hardened S.A.E. 2315 steel worm. These units are used in speed reducers. (Courtesy: Cleveland Worm & Gear Co.)

increasing strength, hardness and wear resistance, the nickel content imparts fine grain and improves the depth of chill, assuring optimum structure all the way to the root of the tooth. Representative mechanical properties of this bronze are included in Table III.

For gears other than worm wheels sand cast bronzes of compositions corresponding to N17 and N18 in Table III are frequently employed. The nickel content of these alloys provides improved toughness and wear resistance, higher compressive strength and better grain structure.

For very heavy duty bronze gearing a heat treatable nickel bronze has been recently developed which can be treated to provide extremely high mechanical properties. The composition which has been found to yield optimum properties comprises 88 Cu, 5 Sn, 5 Ni, 2 Zn and 0.05 per cent P. The excellent properties of this alloy as cast may be immensely improved by means of a heat treatment comprising a quench from a 5-hr. heat at 1400 deg. F., followed by aging for 5 hrs. at a temperature between 500 and 600 deg. F. It is important for proper response to this heat treatment that lead be entirely excluded from the composition. Even as small a quantity as 0.03 per cent has been found to be definitely detrimental. Desirable combinations of strength and ductility can be selected by varying the aging temperature in accordance with Fig. 16. Although the alloy is relatively new,[3] its moderate cost, good casting properties and broad utility have earned it rapid recognition and growing popularity.

TABLE III.—Representative Applications of Nickel Bronzes in Machine Tool Construction.

Application	No.	Nickel	Copper	Tin	Lead	Zinc	Phos.	Tensile Strength, Lbs. per sq. in.	Yield Point, Lbs. per sq. in.	Elongation, Per cent	Brinell Hardness [2]
BUSHINGS AND BEARINGS: (Higher Compressive Strength, Uniform Lead Distribution)											
General	N 1	2.50	80.00	7.50	10.00	0.50 max.	0.04	31,000	18,000	10	75
High strength	N 2	1.50	78.50	10.00	10.00	0.50 max.	0.04	38,000	24,000	15	80
Anti-friction:											
Heavy duty	N 3	1.00	76.00	6.00	16.00	1.00	0.02	29,000	16,000	18	60
Medium duty	N 4	1.00	73.00	6.00	20.00	1.00 max.	0.02	28,000	16,000	12	58
Light duty	N 5	1.50	63.50	5.00	30.00	0.50 max.	0.01 max.	25,000	15,000	9	48
GEARS: (Improved Toughness and Wear Resistance)											
Light load	N17	1.50	85.00	3.50	5.00	5.00	0.03	36,000	15,000	30	71
Heavy load	N18	1.00	87.00	10.00	0.50 max.	2.00	0.05	46,000	22,000	25	78
Worm gears (chill cast)	N19	1.50	87.50	11.00	none	none	0.15	51,000	27,000	18	100
HIGH STRENGTH BRONZE: (High Elastic Properties)											
As cast	N20	5.00	88.00	5.00	none	2.00	0.05	47,000	22,000	45	85
Heat treated [1]	N21	....	....	....	....	....	....	75,000	55,000	20	148

[1] Heat Treatment: 5 hrs. at 1400 deg. F., oil quench, 5 hrs. at 500 deg. F., air cool. Modification of properties can be secured by adjustment of heat treatment. Lead is preferably absent in this composition, for as little as 0.01 per cent of lead will retard the age hardening.

[2] Brinell Hardness obtained with 10 mm. ball at 1000 kg. load.

Conclusion

In this article the authors have endeavored to indicate in a general way the role of nickel in present day machine tool construction. Obviously the complexity of the field and the wide variety of types and sizes of machines which it encompasses prohibit much detail in a single article, but it is hoped that the material presented has given some indication of the major part which nickel is playing in the continued progress of this important and fundamental industry.

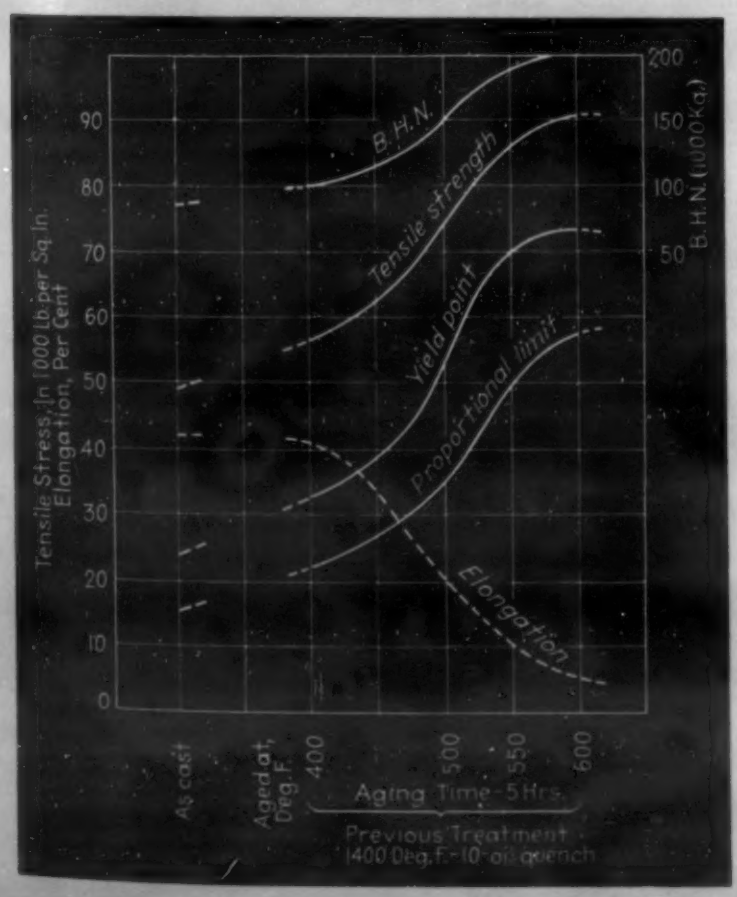
TABLE II.—Representative Applications of Nickel Alloy Steels in Machine Tool Construction.

Description of Part	Chief Service Requirements	S.A.E.[2] Steels Employed [1]	Heat Treatment
Anti-friction bearings	Wear resistance, high compressive strength	4615, 3312	Case hardened
Bolts and studs	High strength, ductility, toughness	3135, 3140, 4640, 2330, 2340	Oil quenched and tempered
Cams	High resistance to wear and spalling	3115, 4615, 2315, 3312, 2515	Case hardened
		3270, 4370	Oil quenched and tempered
		3150, 4640	Flame hardened
Chucks			
Jaws and face plates.....	Wear resistance, strength	4615, 3312, 2515	Case hardened
Pins, center plugs, etc....	Strength and toughness	3140, 4640	Oil quenched and tempered
Clutch parts	Wear resistance, toughness	3250, 2350, 4340, 3270, 4370	Oil quenched and tempered
		4615, 2315, 3312, 2515	Case hardened
Collets and feed fingers.....	Wear and fatigue resistance	4620, 2320	Case hardened
		3270, 4370	Oil quenched and tempered
Gears	Wear resistance, strength and toughness	3140, 3150, 3250, 2350, 4640	Oil quenched and tempered after machining
		3130, 3140, 4640	Oil quenched and tempered before machining
		3115, 4615, 2315, 4320, 3312, 2515	Case hardened
		3140, 4640, 2340, 4340	Flame hardened
Guides	Wear resistance, high strength	4615, 2315, 3312	Case hardened
		3270, 4370	Oil quenched and tempered
Lathe tool holders.....	Strength and toughness	3140, 4640, 3240, 2340, 4340	Oil quenched and tempered
Lead screws	Wear resistance, toughness	3140, 3240	Oil quenched and tempered
Milling and boring cutter bodies	Strength and toughness	3140, 4640, 3240, 2340, 4340	Oil quenched and tempered
With pilots	Wear resistance, strength and toughness	3115, 2315, 3312	Case hardened
Shafting	Torsional strength, toughness	3140, 3150, 2340, 2350, 3240, 3250, 4340	Oil quenched and tempered
	Resistance to wear and galling, torsional strength	3115, 3120, 4615, 2320	Case hardened
Spindles	Torsional strength, toughness	3140, 4640, 3240, 2340, 4340	Oil quenched and tempered
	Resistance to wear and galling, torsional strength	3115, 4615, 2315, 3312, 2515	Case hardened
Worms	Wear resistance, strength, toughness	4615, 2315	Case hardened

[1] Steels mentioned are arranged approximately in order of increasingly severe service. Size is also very important as heavy sections will require higher alloy contents to insure optimum response to heat treatment.

[2] Steels used generally conform to the standard specifications of the Society of Automotive Engineers (S.A.E.). In the following list of compositions those steels marked with an asterisk are not now on the S.A.E. list but follow the Society's system of classification. To facilitate reference average figures are given although steel makers naturally require a permissible range for each element.

Fig. 16. Properties of age hardened 88-5-5-2 nickel bronze.



S.A.E. No.	Approximate Chemical Composition, % C	Mn	Ni	Cr	Mo
Direct Hardening Steels					
2330	0.30	0.65	3.50	....	....
2340	0.40	0.75	3.50	....	....
2350	0.50	0.75	3.50	....	....
3130	0.30	0.65	1.25	0.60	....
3135	0.35	0.65	1.25	0.60	....
3140	0.40	0.75	1.25	0.60	....
3150	0.50	0.75	1.25	0.60	....
3240	0.40	0.45	1.75	1.10	....
3250	0.50	0.45	1.75	1.10	....
*3270	0.70	0.45	1.75	1.10	....
4340	0.40	0.65	1.75	0.65	0.35
*4370	0.70	0.45	1.75	0.65	0.35
4640	0.40	0.65	1.80	....	0.25
Case Hardening Steels					
2315	0.15	0.45	3.50	....	....
2320	0.20	0.45	3.50	....	....
2515	0.15	0.45	5.00	....	....
3115	0.15	0.45	1.25	0.60	....
3120	0.20	0.45	1.25	0.60	....
3312	0.12	0.45	3.50	1.50	....
4320	0.20	0.55	1.90	0.45	0.25
4615	0.15	0.55	1.80	....	0.25
4620	0.20	0.55	1.80	....	0.25

Some Fatigue Problems of the Railroad Industry

by R. W. CLYNE

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American Steel Foundries
Chicago.

This article is the fifth in a series of six on Fatigue of Metals, the first of which was published in our issues of May and June, with the second on "Fatigue Problems in the Aircraft Industry" in the July issue. The third on "Fatigue of Light Metal Alloys" appeared in the August issue. The fourth—"Fatigue Problems in the Electrical Industry"—was published in the September issue.

The origin and general scope of the series was fully outlined in an introductory statement to the first installment of the first article—"Fatigue of Metals—Developments in the United States"—published in May issue, pages 158 to 162.

The author of this article, says that the majority of railroad spring failures are due to progressive fractures. Fatigue failures originate in notches or decarburization. Notches may be formed chemically or mechanically. Corrosion fatigue is touched and the bad effect of surface decarburization is discussed. Other important factors are dealt with interestingly.—The Editors.

THE HOT FORMED MECHANICAL SPRING is one of the highest stressed parts used in railway equipment. Helical springs are frequently designed to a maximum stress of 150,000 lbs. per sq. in. Stresses of this magnitude are not infrequent and may be noted during the analysis when consideration is given to torsion, direct shear, curvature, bending and eccentricity. Experience has shown that, under normal service, the relationship between stress and steel composition is such that alloy steel is advisable if the maximum stress in a helical spring exceeds 140,000 lbs. per sq. in. The common alloy spring steels used in this country for railroad and industrial work are silico-manganese, chrome-vanadium and carbon-vanadium.

The function of the mechanical spring is such that it is continually subjected to cyclic stress and hence, fatigue of metals is a predominant factor in failure and should be a subject of consideration in design and manufacture. The service life of steel springs is usually terminated by the acquirement of excessive permanent set or by fracture caused by fatigue. However, before proceeding to a discussion of the factors which influence the behavior of steel springs to cyclic stresses, I wish to mention certain researches which we have conducted upon the tensile properties of spring steels. Our tests indicate that the physical properties of hardened spring steels are materially influenced by scale formations which arise during the heating operations prior to quenching, by the viscosity and circulation of the quenching medium, by the degree of initial hardness and by the use of aluminum additions to the steel during the process of manufacture.

Progressive Fracture—Majority of Spring Failures

The majority of railroad springs fail by progressive fracture. The fatigue crack almost always originates at some point on the inside diameter of helical springs; the point of origin is always on the tension side of elliptic spring plates and usually at one of the corners. The fatigue resistance of hot formed mechanical springs is largely a reflection of surface conditions and does not seem to be materially affected by changes in the common forms of heat treatment or by variation in steel composition. Heat treatment and composition may influence the service life by

affecting permanent set and resultant incipient surface cracks but, at the present time, the effect of surface conditions on the fatigue limit of heavy steel springs is so great that other effects are comparatively small.

Surface Factors: Notches and Decarburization

The surface factors which most severely affect the fatigue resistance of hot formed spring steels generally fall into two classifications, namely: Notches and decarburization. Both chemically (corrosively) and mechanically formed notches must be considered in the first classification for both are of equal importance. Chemically formed notches are surface discontinuities which result from corrosion during service or from exposure to severely oxidizing furnace atmospheres during heat treatment—usually at excessive temperatures. Mechanically formed notches include all surface discontinuities which result from mechanical operations, either in the rolling mill or the fabricating works. Such surface discontinuities may be observed in the forms of rolling grooves, seams or laps, sledge marks, bar indentations, notches due to rolled-in scale, grinding cracks or severe scratches formed during coiling.

Both chemically and mechanically formed notches are sources of stress concentration and may be the focal points of fatigue fractures. The spring industry seems to have had the utmost difficulty in adjusting itself to the fact that the point in question is one of stress concentration rather than reduction in cross section. Such surface discontinuities as corrosion pits and rolling mill seams cannot be dismissed or ignored because of apparent smallness. It may be taken as a matter of fact that good springs with rough surfaces are figures of speech only. Certain problems of surface condition, such as corrosion and decarburization, are of no simple or apparently immediate solution. It is reasonable to assume, however, that such problems cannot be solved until more widespread appreciation of their very existence is gained.

Notches Formed Mechanically

Mechanically formed notches offer possibilities of elimination in the very near future by means of proper equipment and production and testing methods. Rolling seams and other mill defects may be both deep and sharp and may lead to early spring failure under cyclic stresses. Such defects may be promptly identified by use of the acid etch or magnetic testing equipment. Sledge marks, bar indentations and longitudinal coiling scratches may be eliminated by the substitution of powerful and automatic coiling equipment for obsolete manual machines. Mechanically formed notches may originate along the surfaces of the inside diameter of helical springs during the coiling operation by the rolling or forcing-in of thick oxides which are largely formed during exposure of the bars to excessive temperatures prior to coiling. Comparative freedom from this type of defect may be gained by the use of furnaces subject to close and automatic control, operated at reduced temperatures which are allowable if high speed and powerful coiling equipment is available. The removal of mechanical notches formed during mill rolling by means of bar grinding is probably of questionable value, for in this process the protective effect of the mill scale is lost and the usual result is the formation of large volumes of free ferrite during subsequent heating operations.

Certain forms of mechanical notches have been deliberately introduced in designs without realization of possible damaging effects as sources of stress concentration due to their shape or location. For example, spherically shaped impressions (nibs) have been hot formed in top and bottom plates of elliptic springs at the sides of the center band in an effort to prevent the rare occurrence of slipping of the band in service. Frequent spring failure resulted and analysis of the design showed that nominal surface stresses had been increased 100 per cent theoretically, due to the presence of the spherically shaped impressions.

The subject of mechanically formed notches in railroad springs could be pursued further, but without affecting the conclusion that such surface discontinuities reflect faulty production equipment or methods, or faulty original designs. American railroads are becoming increasingly aware of the losses sustained through fractures originating in mechanically formed notches and are beginning to insist upon the elimination of such defects.

Notches Formed Chemically

The first type of chemically formed notch to be considered is a result of severe surface oxidation caused by the use of excessive temperatures and improper atmospheres in bar heating furnaces. The defect occurs in the form of irregular pits which may extend over the entire surface of the bar. This condition is usually formed on bars of large cross-section which, in the absence of powerful and high speed coiling equipment, must be heated to excessive temperatures for long periods, if the coiling operation is to be accomplished in one heating and with accuracy and precision. Fig. 1 is a photograph taken at 100 magnifications on the unetched cross-section of a hot wound spring of large bar diameter which clearly illustrates the extreme surface roughening resulting from the use of excessive temperatures such as 2000 deg. F. Fig. 2 shows the comparatively smooth surface which is obtained on bars of large diameter when bar heating temperatures are in the range of 1575-1600 deg. F. Long springs, of large bar diam-

Fig. 1. Unetched cross-section of a hot wound spring of large bar diameter which clearly illustrates the extreme surface roughening resulting from the use of excessive temperatures. 100X.

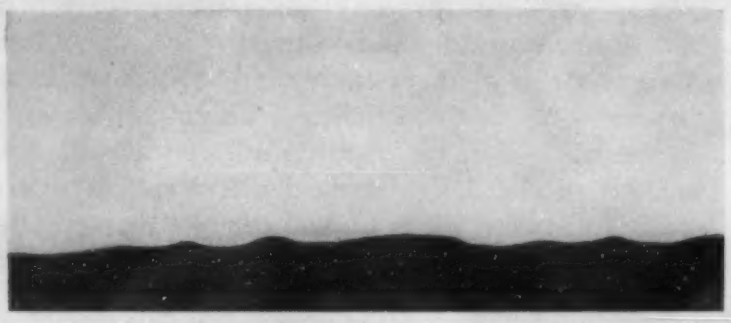


Fig. 2. The comparatively smooth surface obtained on bars of large diameter when bar heating temperatures are from 1575 to 1600 deg. F.

eter, can be accurately and rapidly coiled at low temperatures, providing that the equipment available is of the necessary strength and speed. In the absence of such equipment, severe surface roughening from exposure to high temperatures may be expected.

The majority of heavy railroad and industrial mechanical springs are exposed to corrosion during service. Stress-corrosion occurs in all service in which dynamic stress and corrosion proceed simultaneously. It is probable that with increasing general appreciation of the fundamental behavior of steel springs to corrosive conditions, many of the failures which still occur apparently "without cause" will be clarified.

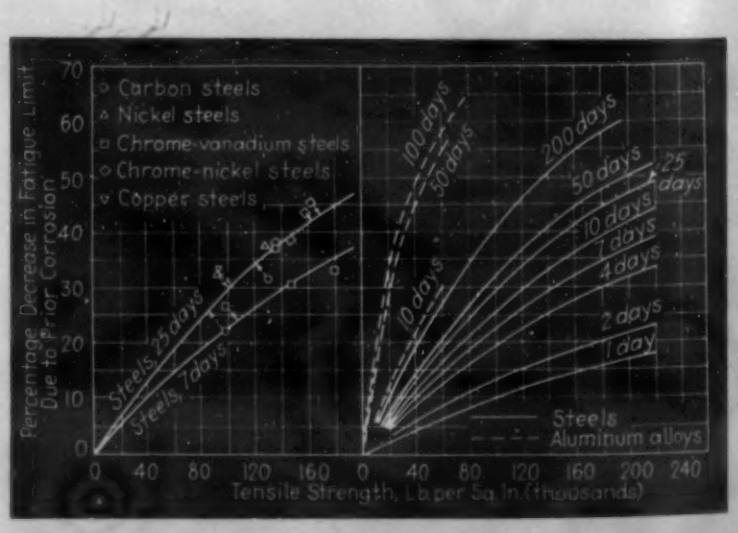
Corrosion Fatigue

Many of the various aspects of corrosion-fatigue have been thoroughly investigated by Dr. D. J. McAdam, Jr., metallurgist, National Bureau of Standards, Washington, D. C. These researches have been conducted upon machined and polished specimens of ferrous and non-ferrous metals in a wide range of composition, treatment and properties, and detailed consideration was given to the influence of stress range, cycle frequency, water composition and oxygen concentration.

The seriousness of the general problem of corrosion of steel which is subject to cyclic stress may be appreciated from observation of Fig. 3[1]. The figure shows the percentage reduction in fatigue strength (rotating cantilever) of machined and polished specimens[2], of aluminum alloys and carbon and alloy steels (not of the corrosion-resistant types) due to stressless corrosion in carbonate water from periods indicated in days on each individual curve. For example, the fatigue limit of machined and polished steels of 200,000 lbs. per sq. in., tensile strength (spring steel strength) is reduced about 32 per cent following four days subjection to carbonate water corrosion. In Fig. 3 the composite curves for aluminum and steel alloys deal with the effect of stressless-corrosion with strength variation of test specimens due to composition and heat treatment only and are not concerned with strength variations due to cold working.

In steel springs, however, as contrasted with carefully machined laboratory specimens, the issue is complicated by the presence of surface decarburization and, in the absence of research data, the possible corrosion effects have been controversial. Our first step, therefore, in dealing with the general corrosion problem was to establish the general effect of decarburization and free ferrite. To this end, we began our tests on full size helical railroad springs which were subjected simultaneously to 3 per cent sodium chloride solution sprays and cyclic stress of 44,000 lbs. per sq. in. range. Due to machine limitations we were forced to confine our investigation of helical springs, with and without corrosion, to this stress range. These tests indicated that, under the specific test conditions, the springs had an average life of 300,000 cycles to fracture when subjected to corrosion-fatigue, and that, in the absence of corrosion, failure was not encountered at 2,000,000 cycles, at which point the tests were discontinued.

Fig. 3. Composite curves for aluminum and steel alloys.



We therefore concluded that corrosion-fatigue was an extremely active agent of destruction despite the presence of decarburization at the surface of the test specimens. Microscopic examination of the failed helical springs indicated that the early failures were due to the rapid formation of sharp and deep stress-corrosion pits and cracks of the type shown at 100 magnifications in Fig. 4. The general surface appearance of one of the test springs which failed in corrosion-fatigue may be seen in Fig. 5. It is interesting to observe that only corrosion pits formed on the outside diameter and low stress regions of the spring, while minute stress cracks propagated from the corrosion pits and joined together to form large cracks on the inside diameter and higher stressed regions of the spring.

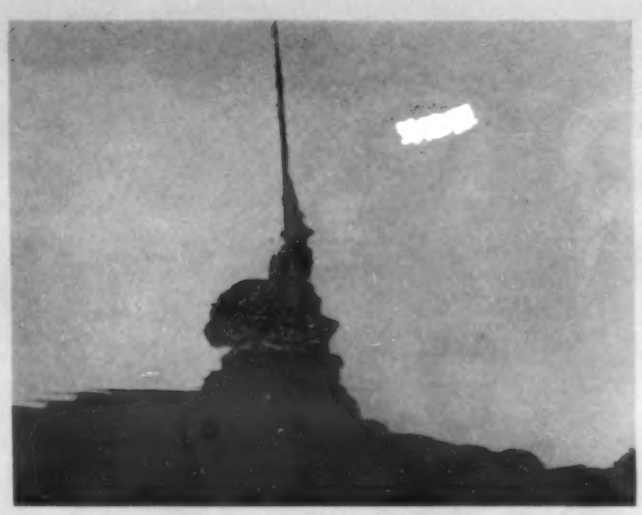


Fig. 4. Rapid formation of sharp and deep stress-corrosion pits and cracks. 100X.

Failures of Elliptical Springs

Some time ago our attention was directed to numerous failures of elliptic springs which were occurring on an American refrigerator line after about one year of service. Microscopic examination of the failed plates indicated the general surface condition which is shown in Fig. 6 at 100 magnifications. The figure clearly shows the presence of fatigue cracks which, in all cases, originate in corrosion pits. In an effort to duplicate and further determine this corrosion effect, we subjected full size carbon and alloy steel elliptic springs to stressless-corrosion by means of intermittent dipping in concentrated sal-ammoniac solution for a period of 30 days. Following this treatment the springs were dried and tested in fatigue to fracture.

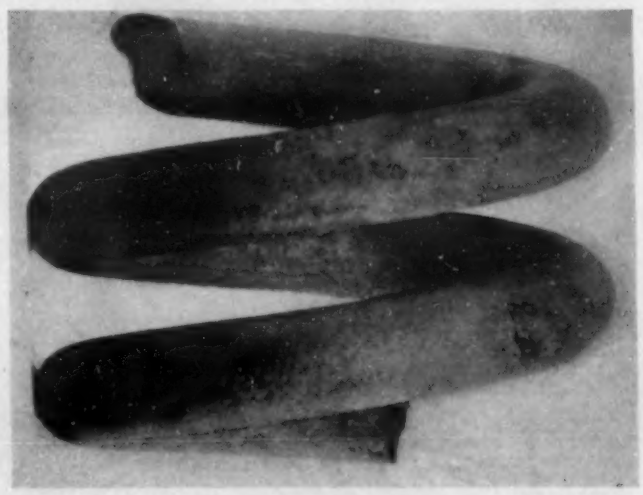


Fig. 5. General surface appearance of one of the test springs which failed in corrosion fatigue.

As expected, early spring failure was encountered. It was concluded that the service failures were a result of corrosion-fatigue and sharply increased nominal stress due to stiffening of the spring with accumulation of corrosion products. The problem was solved by the development of a snubber which employed a combination of low stressed steel helical springs and rubber springs. The surface condition of one of the laboratory chrome-vanadium elliptic spring plates used in this investigation is shown in Fig. 7. The photograph shows the shallow and dish shaped corrosion pits which are typical of stressless-corrosion. The stress concentration at the base of these pits is sufficient to develop fatigue cracks under nominal and cyclic surface stresses. Such cracks propagate rapidly and it may be observed that the photograph shows a corrosion crack extending into the line of fracture.

Fig. 6. General surface condition of failed plates. 100X.

We are convinced that the corrosion problem of steel springs in service is a serious one and that it is accountable for many of the service fractures which occur despite the exercising of the utmost manufacturing precautions. No immediate and practicable solution is apparent at this time. The problem is a

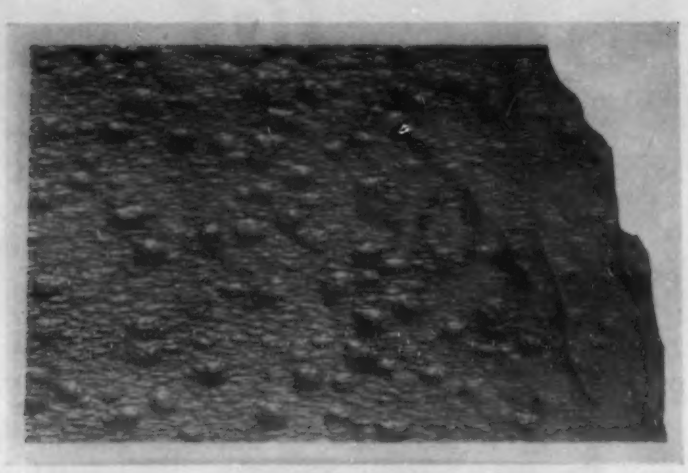


Fig. 7. Surface condition of one of the laboratory Cr-V elliptic spring plates used in the investigation.

joint one and it is probable that ultimate solution will be dependent upon cooperative research between the railroads and the spring manufacturers.

Bad Effect of Surface Decarburization

Surface decarburization appears to cause greater reduction in the fatigue limit of hot formed steel springs than any factor which is introduced or subject to possible control during the entire sequence of manufacturing operations. Researchers at the National Physical Laboratory, Teddington, England, have exposed quite clearly the detrimental effects of surface decarburization on the fatigue of spring steels. Fig. 8 is a composite diagram assembled from British data[3, 4] on carbon and alloy spring steels, which illustrates the effect (ascribed to decarburization) of usual furnace atmospheres on spring steels. The upper curve represents the intrinsic fatigue strength of the steel considered (machined and polished flat specimens). The lower curve shows the fatigue strength of the steels as affected by surface conditions resulting from furnace atmospheres (specimens in the "as heat-treated" condition).

The researches were extended to show that the differences in fatigue limits were not due to surface discontinuities; apparently, the loss in strength was a result of decarburization. Our preliminary researches, in repeated bending, indicate that the fatigue limit of our plain carbon spring steel is increased about 65 per cent if the decarburized surfaces are removed by grinding. Inasmuch as Fig. 8 presents data which are the results of investigations of carbon and alloy spring steels of wide hardness ranges, particular note should be made of the fact that the fatigue strength increases due to hardening by heat treatment or composition variation are but a fractional part of the strength increases which result from elimination of the decarburized volumes.

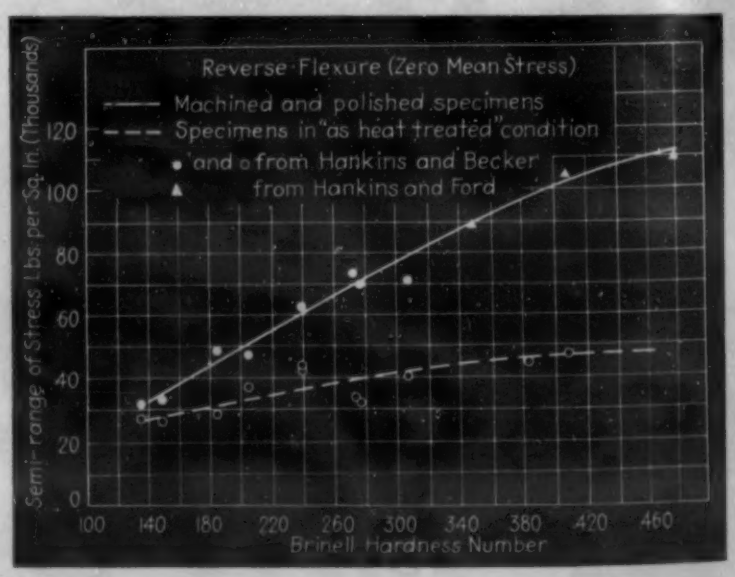
Relative decarburization is largely a function of temperature, atmosphere and steel analysis. Carbon spring steels tend to decarburize less than silico-manganese steels, but the latter have superior elastic physical properties and offer the greater resistance to permanent set. There is little difference in the fatigue limits of the ordinary alloy or carbon spring steels when tested with full effect of average surface conditions resulting from heat treatment.

British investigators have been exploring various possible methods of effective control of surface layer carbon during the various heating operations to which steel is subjected in the manufacture of springs. This work has developed certain laboratory processes which show that spring steel can be so treated that previously noted losses in fatigue strength due to decarburization may be eliminated. It seems reasonable to believe that some economical method of control of surface layer carbon during the heating cycle for grain refinement will be developed and that this method will be adaptable to large scale spring production. However, we believe it essential to anticipate this practical development by immediate adjustment in production methods which will tend to prevent the formation of free ferrite during the bar heating operations.

High Temperatures and Free Ferrite

Again, the attention must be directed to the high temperatures commonly used during this operation for the largest formations of free ferrite occur at this point in the production cycle. Fig. 9, taken at 100 magnifications, is typical of the extent of decarburization and free ferrite in plain carbon spring steels following the use of excessive temperatures prior to coiling. The particular specimen of 1¾-in. round steel had been air cooled following coiling from 2000 deg. F. The total effective depth of de-

Fig. 8. Composite diagram assembled from British data on carbon and alloy steel springs.



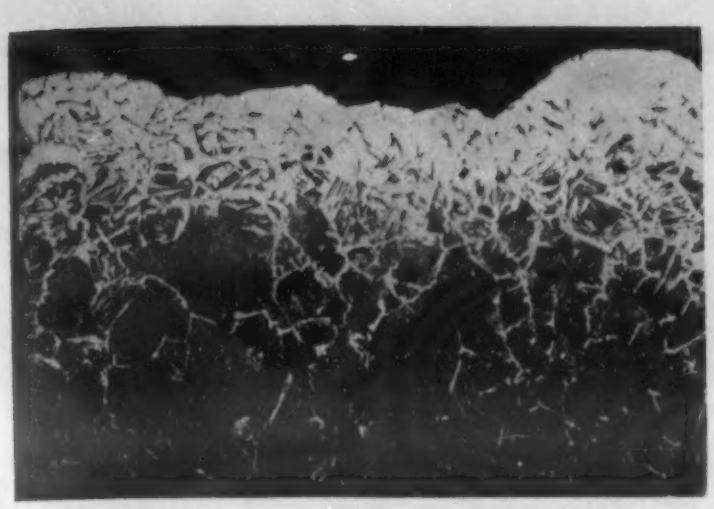


Fig. 9. Extent of decarburization and free ferrite in plain carbon spring steels following the use of excessive temperatures prior to cooling. 100X.

carburization is about 0.0175 in. and the depth of free ferrite is about 0.003 in. This condition may be improved to a considerable degree by the installation of mechanical equipment which will allow for high production coiling in the range of 1575 to 1600 deg. F., as shown in Fig. 10 at 100 magnifications. The specimen had been air cooled following coiling from 1600 deg. F. The photograph shows the smoother surface condition, the absence of free ferite and the reduced depth of total effective decarburization. In the hardened condition, steel of this structure will show zero depth of apparent decarburization.

During recent investigations of plain carbon spring steels, our research laboratory observed hardness differentials between surface and interior layers in quenched and tempered specimens which were free of decarburization. Investigation showed that the reduced surface hardness was a reflection of initial hardness following quenching. The condition appeared to be due to the different constituents which are formed when the specimens are quenched to a high degree of initial hardness. When spring steels, especially those having small sections, are quenched in oil, the microstructure near the surface will in many cases be partially martensitic, while the structure farther away from the surface will contain no martensite. After a drawing operation, the martensitic structure near the surface will be decidedly changed, and the hardness may be reduced to a lower point than is found at some distance from the surface.

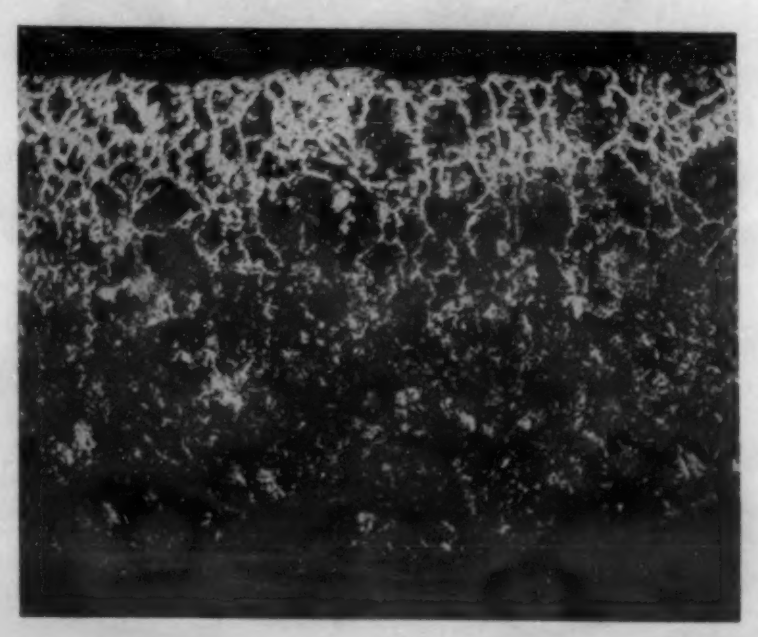
The Car Wheel and Fatigue

The railroad car wheel offers some interesting problems concerning fatigue of metals, particularly with respect to the development of shell-outs and thermal cracks. During the past 15 years service requirements have increased severely. Static wheel loads at the rail have increased from about 25,000 lbs. maximum to as much as 35,000 lbs. and impact loads have increased enormously with operating speeds. Limitations in car design have not permitted proportionate increase in the area of contact between wheel and rail and, in general, wheel loads have not reflected lower car body weights. This combination of service conditions has resulted in increased disintegration of tread metal due to fatigue. This disintegration is commonly called a shell-out. The defect occurs by means of progressive fracture and is usually found in comparatively soft wheels which are operating under heavy axle loads. The fracture may originate at the surface or at some sub-surface non-homogeneity, and is due to a combination of effects of stress concentration and static and impact loads. Continued repetition of the loading cycle results in spread of the original crack into a semi-spherical cavity by means of progressive fracture. It is our belief that the greatest resistance to the formation of this type of defect can be offered by wheels of increased tensile strength which are of such metallurgical structure that no definite planes of weakness exist. The increase in strength, however, should not be at the expense of impact properties and ductility.

The Thermal Crack

Our hypothesis is that the thermal crack is a direct result of cyclic tensile stresses which are induced in thin layers of tread metal subjected to repetition of restricted expansion caused by temperature differentials due to severe braking at high speeds. Structural changes in the surface layers of some returned wheels indicate the previous existence of high temperatures followed by rapid cooling, resulting from

Fig. 10. Effect on decarburization and free ferrite of mechanical equipment which will allow for high production cooling at 1575 to 1600 deg. F. 100X.



high speed wheel revolution and metal conductivity. Repetition of the momentary heating cycle and of the condition of restricted metal expansion eventually result in the accumulation of tensile stresses which are sufficient to instigate the transverse thermal crack.

While experience has shown that added resistance to thermal cracks may be offered by wheels of lowered hardness, a rather careful balance must be obtained if shell-outs are to be avoided. Introduction of compressive stresses to the tread metal during manufacturing heat treatment probably resists and delays the formation of thermal cracks. Under conditions of heavy axle load, high speeds, and localized high rim metal temperatures due to braking, it is doubtful if any practical wheel steel will be developed which, due to strength or alloy, will prevent the initial development of such cracks. The problem seems to be one of developing an alloy or a stress condition or both which will resist the propagation of the cracks. Normal wheel wear may be sufficient to continuously remove the small initial crack. The formation and propagation of thermal cracks are essentially fatigue phenomena and it seems reasonable to assume that development of an alloy highly resistant to notch propagation should be on the basis of work hardening capacity. Under service conditions which lead to thermal cracking, the only immediate solution to the problem seems to be to relieve the wheel of part of the static load and applied braking loads probably by means of increase in the number of wheels per unit.

Fig. 11. Wheel and axle unit, adapting the use of roller bearings to the existing designs of railway trucks shown in this phantom view.

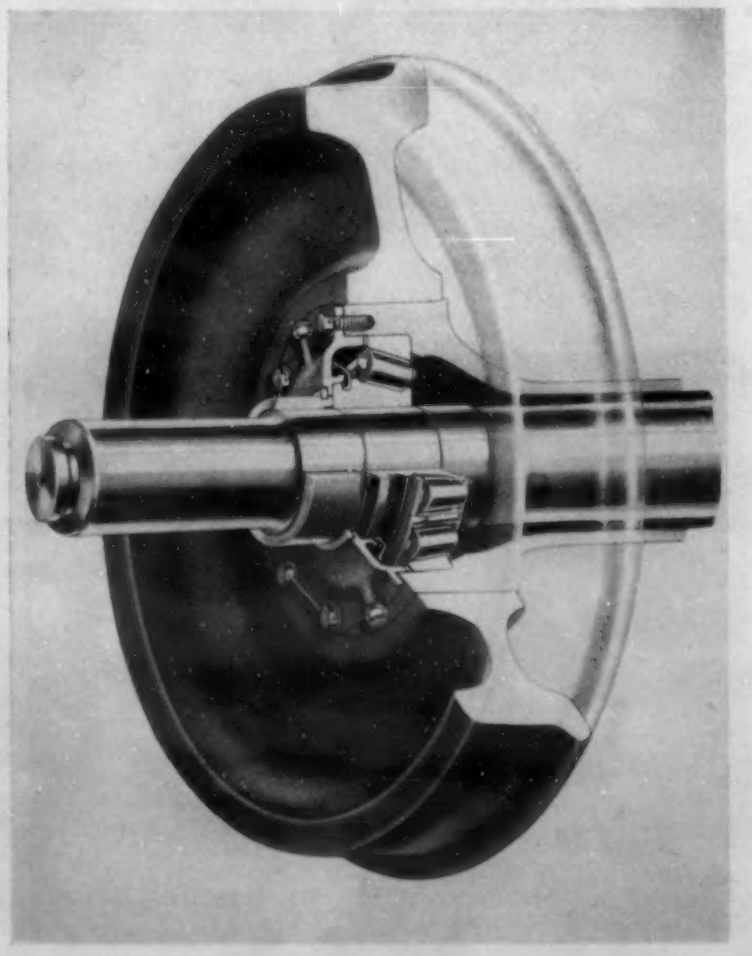


Fig. 12. A number of roller bearing units of the American Steel Foundries.

Fatigue Failures of Railway Axles

Problems in fatigue failures of railway axles were developed on our railroads with the introduction of high speed passenger traffic operations. When roller bearings were first installed in journal boxes, their attachment to the conventional standard axles resulted generally in shorter axle life. This seems to have been caused by a combination of effects due to the greater truck rigidity encountered by such roller bearing applications, greater impact forces resulting from higher speeds and, more particularly, localized fiber stresses due to the rigid press fit mounting of the roller bearing race-way in addition to the wheels on the revolving axle.

The American Steel Foundries, having 35 years experience in railway truck designs, undertook the development of a roller bearing wheel and axle assembly with the object of producing an installation that would be interchangeable with standard wheels and axles and could be handled as a compact unit. The basis of this development was reduction in the fatigue element by virtual elimination of axle revolution and by the separation of the forces resulting from vertical and lateral loads.

This wheel and axle unit, adapting the use of roller bearings to the existing designs of railway trucks and shown in a phantom view in Fig. 11, is arranged so that the two wheels, mounted on a hollow outer housing, revolve around a stationary inner axle member of similar design to the prior standard axle used with friction bearings. This installation of roller bearings permits the same lateral freedom and universal joint type of connection between the journal and the truck frame as the old standard friction

bearing arrangement. At the same time the design provides a fixed mounting for the roller bearings, allowing them to be operated with close running clearances and without serving as a means of holding the wheel and axle assembly in the truck frame. This roller bearing unit having the wheels mounted on a tubular member surrounding the axle relieves the latter of the forces due to lateral wheel flange pressure and the localization of stresses resultant from mounting the wheel hubs directly on the axle.

The tubular member on which the wheels are mounted is stressed only by the lateral forces against the wheel flanges and the axle itself serves merely as a beam receiving the load from the truck side frames and being supported by the roller bearings mounted in the wheel hubs. By this double axle construction a separation of the forces due to vertical load and those

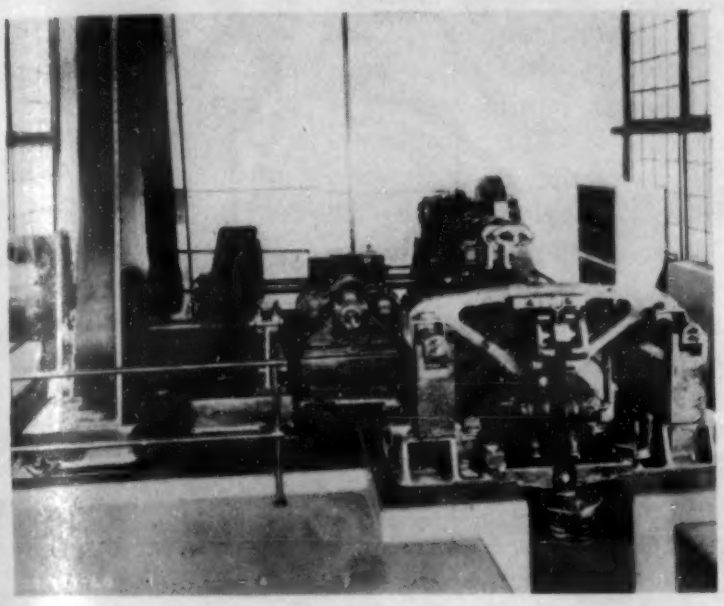


Fig. 13. A fatigue testing machine.

due to lateral load is obtained which prevents combinations of force causing excessive stresses when encountering truck irregularities at high speed. While the axle is normally stationary, it is not rigidly held against rotation. In operation the axle creeps in rotation at the rate of about 2 to 14 revolutions per 100 miles, thereby distributing the wear on the stationary roller bearing race-way but not receiving the rapid stress-reversals encountered with an axle on which the wheels are rigidly mounted.

Fig. 12 is a photograph of a number of American Steel Foundries roller bearing units which illustrate the close resemblance of this design to the conventional friction type wheel and axle assembly. Inasmuch as the unit is loaded through the standard journal box and brass arrangement, this auxiliary bearing may be automatically employed to bring the car into the terminal in case of roller bearing failure.

A Fatigue Testing Machine

In conclusion, I wish to present in Fig. 13 a photograph of a fatigue testing machine which represents one of the most important railroad engineering developments since the introduction of the cast steel side frame. Service failures of this truck part are practically unknown today and this present degree of excellence is largely due to the continuous and progressive fatigue testing which has been carried out on this machine since 1921.

Road tests originally traced the failures of the early designs of cast steel side frames to the fact that transverse and twisting loads had not been considered in the stress analysis. More definite data regarding live vertical loads were also gained during these tests. Development of the Berry strain gage, static testing machines which applied the three primary loads to the test frames, and added data regarding the location of service failures indicated the presence of secondary service stresses. Therefore, the fatigue machine for the testing of full size cast steel side frames was developed in order to simulate service conditions and enable us to compensate for weaknesses with better metal distribution.

Castings are generally tested at a machine speed of 25 r.p.m., which results in 50 applications of vertical loads, 100 applications of transverse loads and 50 applications of twist loads per minute. The magnitude of the loads applied to the casting under test are as follows:

Vertical load ..... 250 per cent of axle capacity.
Transverse load .....32.5 per cent of axle capacity.
Twist load .....21.3 per cent of axle capacity.

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[3] Hankins, G. A. and Becker, M. L. "The Effect of Surface Conditions Produced by Heat Treatment on the Fatigue Resistance of Spring Steels," *Journal* of the Iron and Steel Institute, No. 2, 1931.

[4] Hankins, G. A. and Ford, G. W. "The Mechanical and Metallurgical Properties of Spring Steels as Revealed by Laboratory Tests," *Journal* of the Iron and Steel Institute, No. 1, 1929.

Supplementary Note

to the Article on Low Lead-Silver Alloys for Bearings (Page 306)

Since the above paper was written, some evidence has been received which should be considered at the same time as the paper. Specifically, some tests of electrodeposited silver-lead alloys have been made on a machine which simulates the action of an engine.

Two full size silver master rod bearings were bored oversize by Pratt & Whitney Aircraft Co., and sent to Battelle for electroplating. They were plated with an excessive thickness of a silver-lead alloy, and given an annealing treatment of 5 hrs. at 500 deg. F., followed by 4 days at 350 deg. F. The bearings were then returned to Pratt & Whitney where they were bored to the correct size. They were then tested in a bearing testing machine, in which the test bearing is loaded by the inertia of a revolving eccentric weight, similar in principle to the well known General Motors type of bearing testing machine. A letter from Mr. Ryder, of Pratt & Whitney, describes the results as follows:

"The routine (of test) is to run the bearing for 1½ hrs. at 1350 r.p.m., ½ hr. at 2000 r.p.m. and then add 50 r.p.m. every 2 mins. until seizure occurs, or until the capacity of the motor is reached. This is about 3950 r.p.m. The bearing is fed with oil at 100 lb. per sq. in. and 160 deg. F., using our engine oil which is 100 seconds Saybolt at 210 deg. F. The test machine is arranged so that when the friction torque of the bearing exceeds 83 ft.-lbs., the bearing is allowed to turn with the shaft so that no further destruction occurs. Both of the bearings were fitted with 0.008 in. clearance.

"The C-3 bearing seized at 3400 r.p.m. without very much damage and the C-4 bearing ran to 3700 r.p.m. and shows more smearing of the surface.The bond was not quite perfect in either case."

. . . . "For comparison I will say that the plain silver bearing seizes in this machine at 2650 r.p.m. and upward. The 224 bronze goes out quite reliably at 3000 to 3200 r.p.m. I think we can expect some plain silver bearings to go higher than this, but they are quite unreliable. The 121 bronze can be run up about as fast as the motor will drive it without seizure, but will show fatigue if run for a protracted period."

These results show very positively that the bearing characteristics of silver have been greatly improved by the presence of lead. Further study would undoubtedly reveal the proper method of obtaining the higher seizure resistances of which these alloys are capable. These two bearings, being the first ones plated, cannot be regarded as anything except indicators of what may be expected from the alloy. The evidence is greatly in favor of silver-lead alloys, since they have greater seizure resistance than the strong (224 bronze) copper-leads and greater strength than the seizure resistant (121 bronze) copper-lead. Furthermore, since the results of the Amsler test show that silver-leads can have greater seizure resistance than any other yet tested material, a study of the effect of plating conditions and annealing treatments on seizure resistance would undoubtedly enable the high seizure resistance of cast alloys to be obtained in plated materials.

The seizures may have been caused by the bond failures mentioned by Mr. Ryder. More detailed study of cleaning and plating methods would enable bond failures to be prevented.

A table has been prepared which shows more of the details of the bearings tested and the results of the tests. This table is as follows:

Table of Seizure Resistance of Various Bearing Materials as Determined in the Pratt & Whitney Engine-type of Bearing Tester

Designation of Bearing Material	Approximate Composition	Speed to Obtain Seizure r.p.m.	Bearing Pressure at Seizure, lb. per sq. in.	Remarks
Silver bearing	99.5+% Ag, bal. Cu	2650	3410	
224 bronze	25% Pb, 3% Sn, bal. Cu	3000-3200	4380-4980	Fatigue-resistant bronze
C-3	3.62% Pb, bal. Ag	3400	5620	Electroplate 0.006 in. thick on silver bearing
C-4	3.41% Pb, bal. Ag	3700	6650	Electroplate 0.0025 in. thick on silver bearing
121 bronze	1% Ag, 28% Pb, bal. Cu	Over 3950	Over 7590	This material is not sufficiently fatigue-resistant for continuous service

NOTE:—These tests are made against a finely ground shaft of carburized SAE2512 steel. Because the shaft is ground and not highly polished, a pure silver bearing does not have an extremely high seizure resistance.